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OPTICAL FIBRES FOR SENSORS

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Contents

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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 which may occur simultaneously. Considerable advantages can be gained in sensor applications 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 which have a strong wavelength sensitivity to changes in temperature. This produces the basis for distributed sensors which 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.

8.1. 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 0.85μm, 1.3μm and 1.55μm, while the bandwidth of single-mode fibres can, for all practical purposes, be made almost infinite at wavelengths greater than 1.3μm. However, whilst the great majority of experimental and commercial intrinsic fibre sensors currently employ telecommunications-grade fibres, largely as a result of their ready availability, this policy frequently leads to a design compromise, and in some cases makes the performance marginal or, even untenable, due to excessive environmental sensitivity. Consequently, attention is now being given to the design of special sensor fibres with enhanced (or depressed) sensitivity to specific measurands.

There are few special fibres currently commercially available. Perhaps the best known is the highly-birefringent fibre [Dyott et al 79], both in polarisation-maintaining [Birch et al 82] and polarising [Varnham et al 83a] form. Such fibres are extensively applied to polarisation control in fibre gyroscopes and other sensors, and are also under investigation for use in coherent communications systems [Smith et al 83]. 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 [Varnham et al 85, Li et al

86a] make them very suitable for magnetic-field sensing. Work is also underway on metal/glass composite fibres for the production of polarisers [Li et al 86b] and Kerr modulators [Li et al 86c].

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 [Poole et al 85]. Several laboratories [Millar et al 87, Shimizu et al 87, Po et al 86] 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 1.06, 1.08 and 1.536μm in single-mode fibres, by doping with Pr^{3+}, Nd^{3+}, and Er^{3+}, respectively [Reekie et al 86, Mears et al 85, Mears et al 86]. 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 [Farries et al 86].

It is clear that fibre fabrication technology is now able to offer a number of attractive solutions to the unique problems presented by fibre sensors. A wide range of possibilities are available, including modified telecommunications fibres which are bend resistant, metal [Dandridge et al 80] and special polymer-coated [Koo et al 82] fibres, fibres with liquid cores [Hartog 83] or claddings [Sheggi et al 83], spun low-birefringence fibres [Barlow et al 81] and twin-core fibres [Snitzer et al 82].

This chapter describes the fabrication of fibres with 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.

8.2. FIBRES WITH MODIFIED POLARISATION PROPERTIES

8.2.1 INTRODUCTION TO BIREFRINGENCE

In single-mode fibres, the fundamental HE_{11} mode is linearly polarised. Thus, in theory, if an ordinary single-mode 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 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 many sensor designs, however, the state of polarisation of the modes in a fibre must be strictly controlled. For example, a stable state of linear polarisation is required in fibres for interferometric sensors. Conversely, a Faraday rotation sensor requires the fibre to have either very low linear birefringence, or a high circular birefringence, in order to observe the small field-induced polarisation rotation. These disparate requirements lead to a number of special fibre designs with differing degrees and types of birefringence.

8.2.2 FIBRES WITH NEGLIGIBLE BIREFRINGENCE

The detection of magnetic fields and electric currents through the Faraday effect requires fibres with very low inherent linear birefringence to allow the observation of the small field-induced polarisation rotation. This is particularly the case in the fibre current sensor, where several turns of 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.

Initially, 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. 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 non-circularity must be no greater than 0.06% in order to achieve a retardance of 3°/m. This approach was partially successful and retardances as low as 2.6°/m were achieved, some three orders of magnitude smaller than in a typical fibre [Norman et al 79]. However, the fabrication process was difficult, giving a low yield with usable lengths limited to about 100m.

Another possibility is to average out the linear birefringence in a fibre by twisting it [Ulrich et al 79]. Unfortunately the fibre breaks before the effect becomes useful (i.e. at beat lengths (see Section 8.2.3) of about 10cm) 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 during fibre drawing [Barlow et al 81]. 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 thus be reduced to negligibly low levels [Payne, D.N. et al 82].

External effects, such as bends, pressure, etc., can re-introduce birefringence which is not affected by the spun core. This forms a practical limit to the sensitivity of Faraday rotation sensors fabricated with low birefringence fibres and a better solution where high sensitivity is required is to employ circularly or elliptically birefringent fibres (Sections 8.2.4 and 8.2.5) Nevertheless, spun fibres are particularly useful for measurement of magnetic fields and electric currents, provided the externally-induced birefringence is kept small.

8.2.3 LINEARLY-BIREFRINGENT FIBRES

As discussed previously, a stable state of linear polarisation is required for many fibre sensors. To achieve this, it is necessary to reduce the amount of coupling between the two mode components by introducing strong linear birefringence into the fibre.

One method of doing so is to make the core non-circular in shape so that the refractive-index distributions in the two principal directions are different (Fig 8.1(a)) [Dyott et al 79]. In these form-birefringent fibres, the refractive-index difference between core and cladding must be large, since the birefringence, B, α $(\Delta n)^2$ which means in turn that in order to maintain single-mode propagation the core diameter must be very small. (Typical parameters for B ~ 4 x 10^4 are core size 1 x 2 μm, Δn = 0.03 to 0.04.) This gives rise to problems of fabrication and jointing of the fibre. On the other hand, bending induced losses are reduced and coupling to the non-circular active emission spot of a semiconductor laser is eased; a simple butt connection to a laser diode can have a loss [Dyott 1987, 1984] of only 1.9dB. The transmission loss of this type of fibre has been reduced to 9dB/km at 0.85μm and 2.5dB/km at 1.3μm.

A more common method of producing linear birefringence is to introduce asymmetric stress over the core of the fibre, either by means of an elliptical cladding or, more commonly, by fabricating the fibre with two regions of highly-doped glass located on opposite sides of the core, as in the well-known "Bow-Tie" [Birch et al 82] or PANDA [Sasaki et al 82] fibres (Fig 8.1(b and c)). Linear birefringence is now induced elasto-optically by the different thermal contractions of the doped regions, combined with the asymmetric fibre cross-section. Of the various designs of stress-birefringent fibres, the one producing the largest birefringence is the "Bow-Tie" structure in which the shape of the stress-producing sectors has been optimised to produce the maximum degree of birefringence.

Bow-Tie fibres are fabricated by a modification of the MCVD process (Fig 8.2). 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 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 stress-producing glass in the tube assume the "Bow-Tie" shape.

It is possible to produce a high degree of stress in the preform, typically around $20kg/mm^2$ in the B_2O_3-doped stress-producing regions but 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. During the cooling from the drawing temperature of approximately 2000°C, where the stresses are completely relieved, 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 practical fibre strength and reduce static fatigue [Sammut et al 85].

An alternative fabrication technique is that employed in the fabrication of the so-called PANDA (<u>P</u>olarisation-maintaining <u>AND</u> <u>A</u>bsorption-reducing) fibre. Here, a symmetrical pair of holes are drilled either side of the core in a VAD preform and a boron-doped MCVD preform inserted into each hole. This composite preform is then drawn in the usual way to produce a solid fibre in which the stress-producing sectors are formed by the born-doped MCVD preforms. Similar techniques, using rods doped with Al_2O_3 [Marrone et al 84] and B_2O_3-GeO_2 to provide the stress-inducing regions have also been reported.

In all stress-birefringent fibres, the stress-producing sectors should be as near to the core as possible to obtain maximum birefringence. However, too close a proximity may cause an increased attenuation by interaction with the evanescent field in the cladding. Furthermore, there is a slight temperature dependence of birefringence, as the applied stresses will vary with temperature. The properties of fibres produced by the various fabrication processes are summarised in Table 8.1.

In all highly-birefringent fibres, 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 into, 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, which depends on the polarisation of the transmitted light, 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:-

$$L = \frac{2\pi}{\beta_1-\beta_2} = \frac{\lambda}{B} \qquad (8.1)$$

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

$$B = n_1 - n_2 = (\lambda/2\pi)(\beta_1-\beta_2) \qquad (8.2)$$

Beat lengths as low as 0.55mm ($B = 10^{-5}$) have been measured [Birch et al 82].

The ultimate linear polarisation-holding ability of a highly-birefringent fibre is limited by Rayleigh scatter, which continuously feeds a small amount of power into the unwanted polarisation, and by the fact that the fibre mode is not truly linearly polarised, but exhibits field curvature. It therefore has both a major and a minor (orthogonally-polarised) field component [Varnham et al 84]. The polarisation-holding limits are shown in Fig 8.3, where the polarisation crosstalk is plotted as a function of fibre length. It can be seen that for short fibre lengths the mode-field curvature limits the transmission of ***linearly***-polarised light to an extinction ratio of about -40dB, whereas for a length of 100km the Rayleigh scattering limit is -30dB. (The limitations due to minor field components which are present when measuring the extinction in a short length of fibre with conventional bulk-optics when may be overcome by the use of fibre devices to remove the minor-field components. For instance, a short length of conventional monomode fibre can be used to spatially filter (to -70dB) the minor field components prior to the polarisation analyser or, alternatively, using a fibre polariser (see below) to replace the bulk optic analyser in the measurement.) For comparison, experimental results [Kikuchi et al 86] 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.

This polarisation-holding ability of a highly-birefringent fibre is normally characterised by the so-called h-parameter [Rashleigh et al 83], defined as the fractional power transfer per metre of fibre length. For the PANDA fibre above, the h-parameter is $1.6 \times 10^{-7}\ m^{-1}$, corresponding to an output extinction ratio of -38dB after one kilometre. Note, however, that this figure is dependent on the fibre configuration and packaging and will be worse when the fibre is wound in tight coils or sheathed in badly-designed cables. The h-parameter alone may, for practical applications, therefore, not be a sensible parameter for describing birefringence in fibres.

Recent theoretical work has shown [Payne, F.P. et al 86] that the previous interpretation of the h-parameter is incorrect, since no account was taken of the role of the fibre birefringence in suppressing bend-induced mode coupling. It can be shown that for significant mode coupling to occur, the correlation length of the applied perturbation must be comparable to the fibre beat length, typically a few millimetres. The currently observed levels of polarisation cross-talk cannot, therefore, be due to imperfections within the fibre. They are a consequence of uneven fibre coating and externally applied stresses and bends arising from winding onto a drum. This interpretation is supported by recent measurements on the effects of different fibre coatings on the h-parameter [Kikuchi et al 86].

8.2.3.1 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 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 provide a measure of the external parameter. Thus the characteristic of polarisation-maintaining fibre is that the attenuations of the two polarisation modes are equal but the phase constants are very different.

8.2.3.2 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 rapidly 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 [Varnham et al 83a].

Many designs for such a fibre have been proposed [Varnham et al 83a, Okoshi et al 80, Okoshi et al 82, Eickhoff 82, Birch et al 83] although, currently, the only practical devices available are based on introducing a preferential loss into one mode, either by winding the fibre into a coil, or by fabricating the fibre with an absorbing metal sector aligned to one of the birefringent axes (see section 8.3.3) In the former, the different refractive-index distributions in the two principal transverse planes cause the bending loss edges of the two modes to occur 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 83b]. The wavelength region in which polarising action occurs can also be controlled. The spectral variation of attenuation (dB/km) for the x- and y-polarised modes of a typical polarising fibre is shown in Fig 8.4. The fibre was 500m long and had a beat length of 1.2mm at 633nm and a second-order mode cut-off (V=2.405) at 600nm. Extinction ratios of 60dB have been obtained over a wide (>400nm) wavelength range.

8.2.4 CIRCULARLY-BIREFRINGENT FIBRES

Fibres exhibiting a high degree of circular birefringence can find application in the monitoring of magnetic fields and hence electric current. 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 [Ulrich *et al* 79]. It is then found that the propagation constants of modes polarised in the left-hand, and right-hand, circular directions are different. However, this method is limited, since, as indicated earlier, the fibre will break if one attempts to produce beat lengths shorter than about 10cm.

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 [Birch 87]. Such fibres are fabricated by inserting a normal MCVD preform, containing core and cladding, into an off-axis hole drilled in a silica rod. Whilst the silica rod containing the offset 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 pitch length of a few mm (Fig 8.5). 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 5mm (corresponding to a modal birefringence of $B = 1.3 \times 10^{-4}$) and less have been produced (Fig 8.6.)

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, which are not enclosed by the coil. However the fibre has a larger diameter than normal ($\approx 500\mu m$), because the degree of circular birefringence increases rapidly with helix diameter, and is therefore stiff, restricting applications to coils of 30cm radius or more. Furthermore, the mode axis is at an angle to the fibre axis so that launching is more difficult than with a conventional fibre. Nevertheless the helical-core fibre is otherwise well suited to measurements on power lines.

8.2.5 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. The resulting fibre has a permanent frozen-in rotation of the birefringent axes. The polarisation eigenmodes 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 86]:-

$$L_p' = L_p L_t / \{(4L_p^2 + L_t^2)^{1/2} - 2L_p\} \qquad (8.3)$$

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 10mm. The elliptical mode beat length is shown in Figure 8.7 as a function of the spin pitch L_t for various values of unspun beat length, L_p. Curves for values of the ratio $\eta = 2L_p/L_t$, from 1 to 4 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:-

$$\varepsilon = \tan \{\tfrac{1}{2}\tan^{-1}(2L_p/L_t) \qquad (8.4)$$

At high spin rates ($2L_p/L_t > 2$), the ellipticity approaches unity, and the modes are therefore predominantly circularly polarised. Little quenching of the Faraday effect therefore occurs and the sensitivity (Faraday rotation angle < 20°) differs little from the perfect isotropic fibre ($2L_p/L_t = 0$), for values of $2L_p/L_t$ greater than about 2 (corresponding to a resultant elliptical beat length, L_p', equal to $4.24L_p$.) Thus, to ensure a sufficiently large elliptical birefringence (L_p < 10mm) the unspun beat length L_p must be less than about 3mm. Beat lengths as short as 7.2mm have been produced by this technique, which is sufficient to overcome all but the worst packaging effects.

Current sensors constructed from these fibres give excellent performance and are relatively insensitive to external perturbations caused by temperature and pressure fluctuations. For instance, a 100 turn, 25mm diameter fibre coil has been demonstrated, which, when using reflection techniques and a broad spectrum source to compensate for temperature effects, has a current range of 500A and was detector shot-noise limited to 1mA rms/$Hz^{0.5}$ [Laming et al 88]. It is anticipated that this could be improved to give a sensitivity of 100μA rms/Hz$^{0.5}$, by a suitable choice of light source and optical coupling.

8.3. EVANESCENT-FIELD DEVICES

8.3.1 INTRODUCTION

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. These include grinding off and polishing the cladding, tapering the fibre to cause field expansion beyond the reduced cladding, grinding the preform, prior to drawing, to give a D-shaped fibre and creating a longitudinal aperture inside the fibre at a controlled distance fρom the core during the fabrication process. The techniques for polishing [Bergh et al 80] and tapering [Kawasaki et al 81] fibres are described elsewhere and we will thus concern ourselves only with the modified fibre designs for D-fibres and hollow-section fibres.

8.3.2 D-FIBRES

If the substrate and cladding are removed from one side of a single-mode fibre preform, for instance by planar grinding and polishing of the preform surface, the resulting D-shaped preform can be pulled into a fibre which maintains the same D shape as the preform [Dyott et al 82] (Fig 8.1.(a)) The drawing temperature must be low in order to prevent the glass from flowing and reverting to a circular cross-section. The drawing process has the effect of fire-polishing the ground surface of the glass to give an extremely smooth, low-scatter, surface at which interaction may be obtained. By selecting the thickness of the material left on the preform [Millar et al 86], or by subsequently removing part of the remaining cladding [Dyott et al 87], access can be gained to the evanescent field within the fibre to form fibre couplers and polarisers.

8.3.3 HOLLOW-SECTION FIBRES

In their simplest form, hollow-section fibres are a development of the D-fibres described above and have a single longitudinal aperture at a fixed distance from the fibre core. They are fabricated by grinding and polishing a flat on the starting preform (as for a D-fibre) and then sleeving the preform within a close-fitting jacketing tube. The fibre drawing conditions are then chosen to ensure that the preform and jacketing tube fuse together, leaving a hole, corresponding to the ground section of the preform, along one side of the core. This again fire-polishes the ground surface of the glass to give an extremely smooth, low-scatter, surface.

A particular application has been to metal/glass fibre polarisers [Li et al 86c] in which a metal is incorporated directly into the fibre close to the core, as shown in Figure 8.8. The result is a high-performance metal/glass fibre polariser, produced in continuous lengths, and having an extinction ratio which can be selected by cutting to a given length. The acrylate-coated fibre, illustrated in Fig. 8.8, had an NA of ≈ 0.16, a cut-off wavelength of ≈ 1.25μm and the distance between core and hollow-section was ~ 3μm. The fibre was bonded to a stainless steel syringe containing a tin (48%)/indium (52%) alloy (m.p.≈ 120°C). The syringe and the fibre were heated to ≈ 130°C and a gas pressure of ≈4bar 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 can be handled, cleaved and spliced in a similar manner to a conventional fibre. The extinction ratio of a 5cm length of polariser fibre is around 40dB over a wide spectral window from 1300nm to 1600nm (Fig 8.9.) The temperature stability of these devices has also been measured and they have been shown to be temperature insensitive over the temperature range -40°C to 100°C. The maximum operating temperature is limited by the melting point of the alloy (in this case to ~120°C), but higher temperature operation can be obtained by using alternative alloys.

Both the extinction ratio and insertion loss are proportional to the length and it is theoretically possible to design a polariser with virtually unlimited extinction ratio, at the expense of increased insertion loss. This is important, since in many applications, particularly the fibre gyroscope, a large extinction ratio is essential whilst an insertion loss of one or two 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 the required extinction ratio for lengths varying from a few centimetres to several metres simply by adjusting the core/metal separation. The ultimate limit to the extinction ratio attainable in these fibres is set by Rayleigh scattering, as in a highly-birefringent fibre (see Section 8.2.3.) However, as the polariser may be designed to be very short (1 cm or less), the maximum extinction ratio is expected to be in excess of 100dB.

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 et al 86c], 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 several Mhz has been reported with an applied half-wave voltage of only a few tens of volts.

A further application of the twin side-pit fibre is as a pressure sensor [Xie et al 86]. Here, the holes are filled with the fluid whose pressure is to be monitored and any changes in the fluid pressure is translated into a change in the polarisation state at the output of the fibre. Response times as fast as 1mS have been reported.

8.4. FIBRES MADE FROM MODIFIED MATERIALS

8.4.1 INTRODUCTION

To maintain low transmission losses in the near-infra-red wavelength region, it is necessary to reduce all but the essential glass constituents of optical fibres to an absolute minimum. On the other hand, the number of potential sensor applications for fibres may be increased 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, 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 altering the materials from which the fibre is fabricated, for instance by using non-silica-based glasses, or by introducing small quantities of suitable materials into the core or cladding.

8.4.2 MULTI-COMPONENT GLASS FIBRES

Fibres fabricated from multi-component glasses of low silica content may find many applications when the ultra-low loss of telecommunications fibre is not required. Such applications include fibre sensors and non-linear devices, where the increased performance obtainable in non-silica glasses is more critical than the fibre loss, particularly since only a few metres of fibre is usually required. This is important since the use of non-silica glasses, combined with the rod-in-tube fabrication technique used, usually leads to higher losses than in conventional fibres. Nevertheless, 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. Furthermore, since, for example, the Verdet constant is related to absorption losses in the material, it is possible to optimise the fibre design, by a suitable choice of glass, to obtain sensors with a very high bandwidth owing to the short length of fibre required.

Examples of soft-glass fibres fabricated at Southampton University are shown in Figure 8.10, from which it can be seen that many fibre designs are possible. Single-mode "soft glass" fibres, produced by the rod-in-tube technique, have losses of less than 400dB/km. Additionally, high-birefringence fibres have been obtained with beat lengths of less than 7mm.

"Soft" glass fibres may prove highly attractive 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 [Sudo et al 86].

8.4.3 FIBRES DOPED WITH RARE-EARTHS

8.3.1 INTRODUCTION

By introducing rare-earth ions into the light-guiding regions of the fibre, many interesting devices can be constructed including:-

1. Fibre lasers and amplifiers.

2. Distributed temperature sensors based on
   (a) absorption,
   (b) fluorescence.

3. Fibres with increased Verdet constant.

4. Fibres with increased Kerr effect and non-linear optical coefficients.

Until recently, 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. However, simple and reproducible fibre-fabrication techniques have now been developed which do not significantly increase the fibre loss. These processes allow the uniform incorporation of low levels of rare-earth ions into the core or cladding of many types of optical fibre. The dopants are not limited to the rare-earth elements, and can be extended to any material with a solid precursor material, for instance the transition metals.

These various techniques will be illustrated by describing one based on the MCVD process and developed at Southampton University [Poole et al 85, Poole et al 86, Townsend et al 87]. However, other techniques are also possible [Millar et al 87, Shimizu et al 87, Po et al 86].

8.4.3.2 FIBRE FABRICATION

A major advantage of conventional MCVD fabrication is that, as starting materials, one can use the appropriate material halides which 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 87] is illustrated in Figure 8.11. 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 which 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 which 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 small quantities 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.

The technique is simple, reproducible and can provide single-component, or multi-component, doping of a wide range of materials into the core or cladding of both multimode and single-mode optical fibres. By these techniques, single-mode fibres have been fabricated containing various rare-earths (Nd, Er, Dy, Tb, Ce, Eu, Tm, Yb and Pr) with dopant levels of between 0.2ppm and 3000ppm [Townsend et al 87]. Remarkably, all exhibit windows in which losses are comparable with conventional fibres, despite the close proximity of very high-loss dopant absorption bands (Figure 8.12). Measurements by optical time-domain reflectometry indicate that the dopant is incorporated uniformly along the length of the fibre. The 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 amplifiers and non-linear devices.

8.4.3.3 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 [Snitzer et al 83]. However, the application of this technique to distributed sensors required the development of low-loss rare-earth-doped fibre as 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 by optical time-domain reflectometry (OTDR). The typical temperature-dependence of absorption of a Nd^{3+}-doped fibre , at a wavelength of 600nm, is shown in Figure 8.13. Although the fibre contains only 5ppm Nd^{3+}, a linear change in absorption of 0.2%/°C was found over the temperature range investigated. This represents a 10dB/km variation in fibre loss for a 100°C temperature change. With this fibre, temperature distribution along the fibre could be determined with 2°C accuracy and a spatial resolution of 15m [Farries et al 86a].

Considerable improvements in performance can be obtained with other rare-earth dopants at higher concentrations. This has been demonstrated with fibre containing 1000ppm Ho^{3+} ions. In this way a sensitivity of better than 1°C with a spatial resolution of 3.5m was obtained over the temperature range -200 to 100°C [Farries et al 87].

8.4.3.4. RARE-EARTH-DOPED FIBRE FILTERS

The very large, sharp, absorption bands of rare-earth-doped fibres, combined with the low losses attainable away from these absorptions, suggest that compact, low-insertion-loss wavelength filters with extremely high rejection ratios can be fabricated. Typical applications are in wavelength multiplexing and also in spectroscopy, where very high rejection of the exciting laser is required. As a demonstration of such a filter, a length of Ho^{3+}-doped fibre was able to separate the anti-Stokes spontaneous Raman scattering from the pump wavelength in a short length of fibre [Farries et al 86b]. The fibre had a differential attenuation of ~ 10^9 between the pump laser wavelength (He/Ne at 633nm) and the anti-Stokes Raman line at 616nm. The experimental arrangement is shown in Figure 8.14. A 20m length of single-mode fibre generated forward-scattered anti-Stokes Raman radiation and a 7m length of Ho^{3+}-doped fibre filtered the unwanted pump signal. The resulting Raman spectrum is shown in Figure 8.15, in which the anti-Stokes scattering at 616nm. There is also a weak emission at 684nm (corresponding to the 1183^{-1} Raman line in silica.) Some pump radiation remains, but greater rejection could be obtained, if required, by simply increasing the fibre length. Thus extremely high rejections are possible in rare-earth-doped fibre filters.

8.4.3.5 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 $125\mu m$, 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, tuneable, diode-pumped lasers at various wavelengths to be constructed. Such devices could be of considerable interest as light sources for sensors and measurements. Moreover, it is now possible to construct a wide range of active fibre devices and sensors which exploit the numerous fibre components available, such as 4-port couplers, ring-resonators, polarisers and filters. The very-low loss of the fibre permits the construction of long (1400m has been demonstrated) amplifiers and lasers, as well as non-linear devices and distributed active sensors.

A typical fibre-laser configuration is shown in Figure 8.16. For Nd^{3+}-doped fibres, a lasing threshold as low as 100μW can be obtained by longitudinal pumping with a semiconductor-laser [Mears et al 85]. In an optimised cavity, an output exceeding 6mW at a wavelength of 1088nm has been observed, with a slope efficiency of 40%. Tuning of the output wavelength can be accomplished by substituting a grating for one of the mirrors [Reekie et al 86b] and a tuning range of 92nm (from 1065-1150nm) is possible. This is the most extensive tuning range yet obtained in a Nd:glass laser and compares favourably with that of a dye laser.

Erbium-doped fibre lasers operate between 1530nm and 1555nm, i.e. within the important minimum-loss window for optical communications. The fluorescence spectrum, with a typical tuning curve for an Er^{3+}-doped fibre laser superimposed on it, is shown in Figure 8.17. 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 [Mears et al 86] and has a threshold of only 1.6mW [Jauncey et al 88]. At the time of writing this represented the lowest threshold three-level glass laser reported. The recent demonstration of a diode-pumped Er^{3+} fibre laser [Reekie et al 87] 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 [Reekie et al 86c]. The mechanism is one of saturable absorption and has many potential applications including optical memories, switching and amplification.

Q-switching of fibre lasers, with an acousto-optic modulator or rotating chopper, is also possible and peak powers of up to 250 watts have been observed in pulses ranging from 50ns to 1μs in duration. In particular, it is possible to obtain pulses in excess of 100W from a diode-pumped Nd^{3+} fibre laser, a performance which will find many applications in fibre sensors.

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 [Lin et al 87], and fibre gratings to reduce the output linewidth [Jauncey et alw 86]. In addition, a number of novel resonant configurations are possible which obviate the need for dielectric mirrors [Payne, D.N. 87, Miller et al 87]. 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 high-power source for fibre OTDR measurements and as a broadband emitter for the optical-fibre gyroscope.

8.4.3.6 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 [O'Mahoney et al 85] 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 [Mears et al 87]. The amplifier (shown schematically in Figure 8.18) 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 [Mears et al 88]. 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.

8.5. CONCLUSIONS

A wide variety of new optical fibre materials and structures are available which may lead to many different types of sensor application. The examples outlined in this chapter 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.

8.6. ACKNOWLEDGEMENTS

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Fibre Type	Modal Birefrin-gence B (x10^4)	Polarisation Holding Parameter h (x10^{-6}/m)	Minimum Loss (dB/km)	Minimum Loss Wavelength (μm)
Elliptical Core[1]	4.0	10	9	0.85
Bow-Tie[2]	4.8	1	<1	1.55
PANDA[3]	3.15	0.5	0.22	1.55

(1) Dyott, 1987
(2) Birch et al, 1982
(3) Kikuchi et al 1986

Table 8.1 Characteristics of polarisation-maintaining fibres.

FIGURE CAPTIONS

Fig.8.1 (a) Photomicrograph of D-shaped Elliptical-core fibre

(b) Photomicrograph of Bow-Tie fibre

(c) Photomicrograph of PANDA fibre

Fig.8.2 Fabrication of Bow-Tie fibre[2]

(a) Deposition of $F/P_2O_5/SiO_2$ buffer layer and B_2O_3/SiO_2 stress-producing layer in a rotating tube.

(b) Etching of deposited B_2O_3/SiO_2 layer withe fluorine gas in a stationary tube.

(c) Conventional deposition of cladding and core layers.

(d) Controlled collapse under pressure to give distinctive "Bow-Tie" shape of stress-producing sectors.

Fig 8.3 Polarisation-holding limits in highly-birefringent fibre. Note that in short fibre lengths, the crosstalk is dominated by the minor field component whilst in long lengths Rayleigh scatter is the limiting component. The effect of different fibre coating designs is also shown by the three solid lines.

Fig 8.11	Vapour-phase process for fabrication of rare-earth-doped fibres. The second (stationary) burner is used only to purify the dopant precursor and during the core deposition process.
Fig 8.12	Loss spectrum of fibre doped with 800ppm Nd^{3+} ions. The absorption bands visible are typical of the Nd^{3+} ion in a glass host. Note the regions of extremely low loss away from the absorption bands.
Fig 8.13	Temperature dependence of absorption of a Nd^{3+}-doped multi-mode fibre at 600nm.
Fig 8.14	Experimental configuration for fibre filter. The length of Ho^{3+}-doped filter fibre was 7m giving a pump rejection of $>10^9$.
Fig 8.15	Transmission of fibre filter showing both pump rejection and Raman transmission
Fig 8.16	Fabry-Perot configuration for diode-pumped fibre laser. The exact mirror reflectivities are chosen to suit the fibre under investigation.
Fig 8.17	Laser tuning curve and fluorescence spectrum for Er^{3+}-doped fibre laser.

Fig 8.18 Schematic representation of a doped fibre amplifier The pump laser and coupler characteristics are chosen to suit the properties of the doped fibre.

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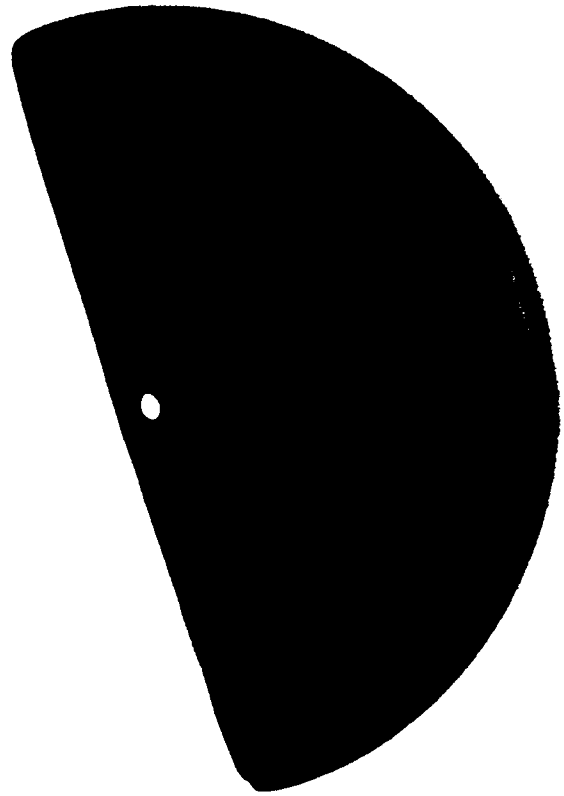

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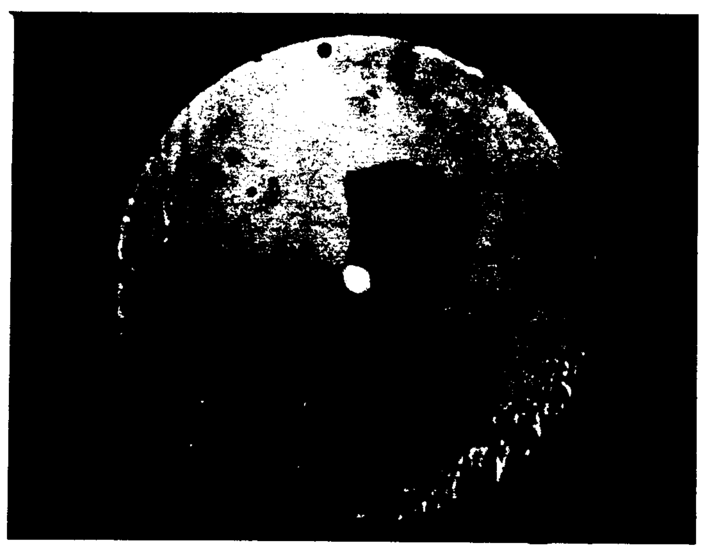

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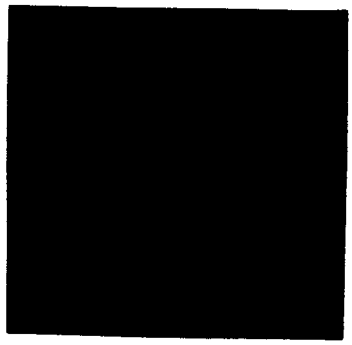


fig 1 (c)

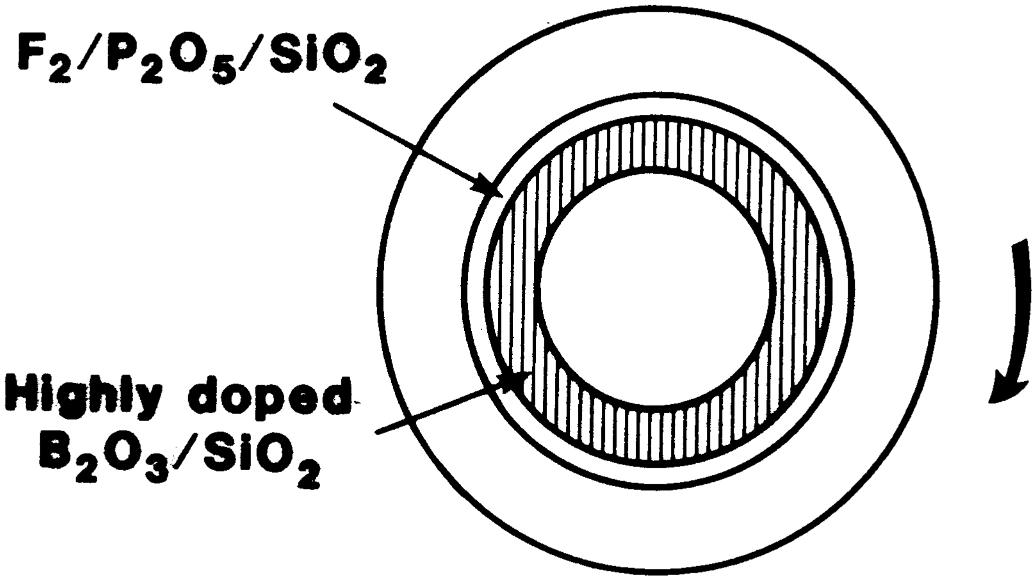


Fig 2

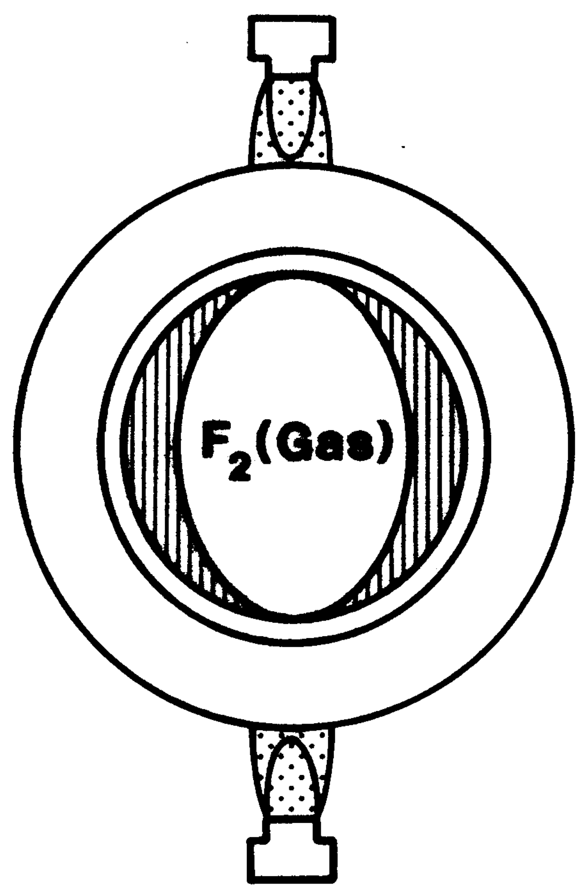
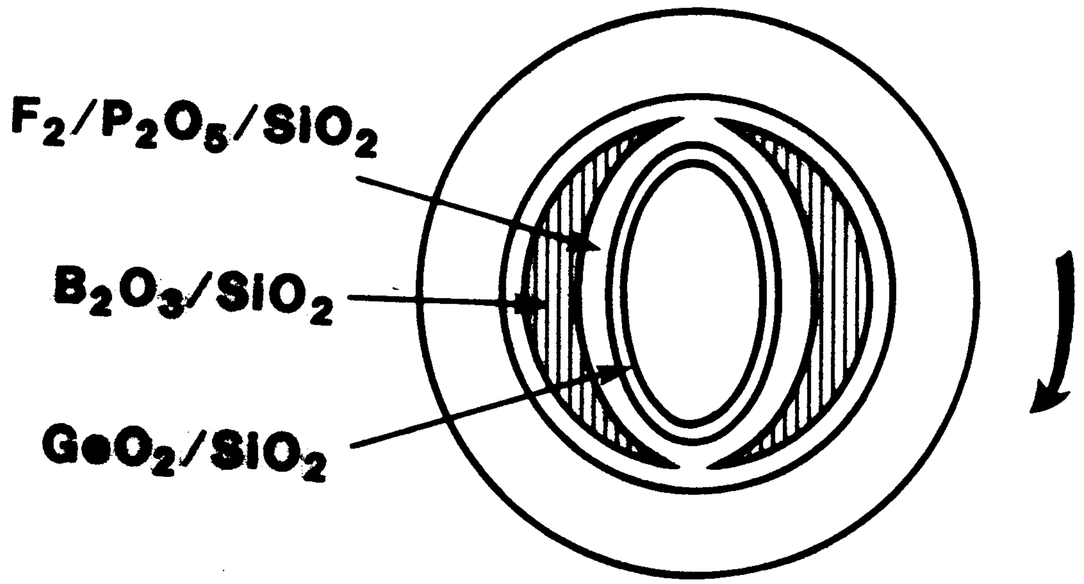
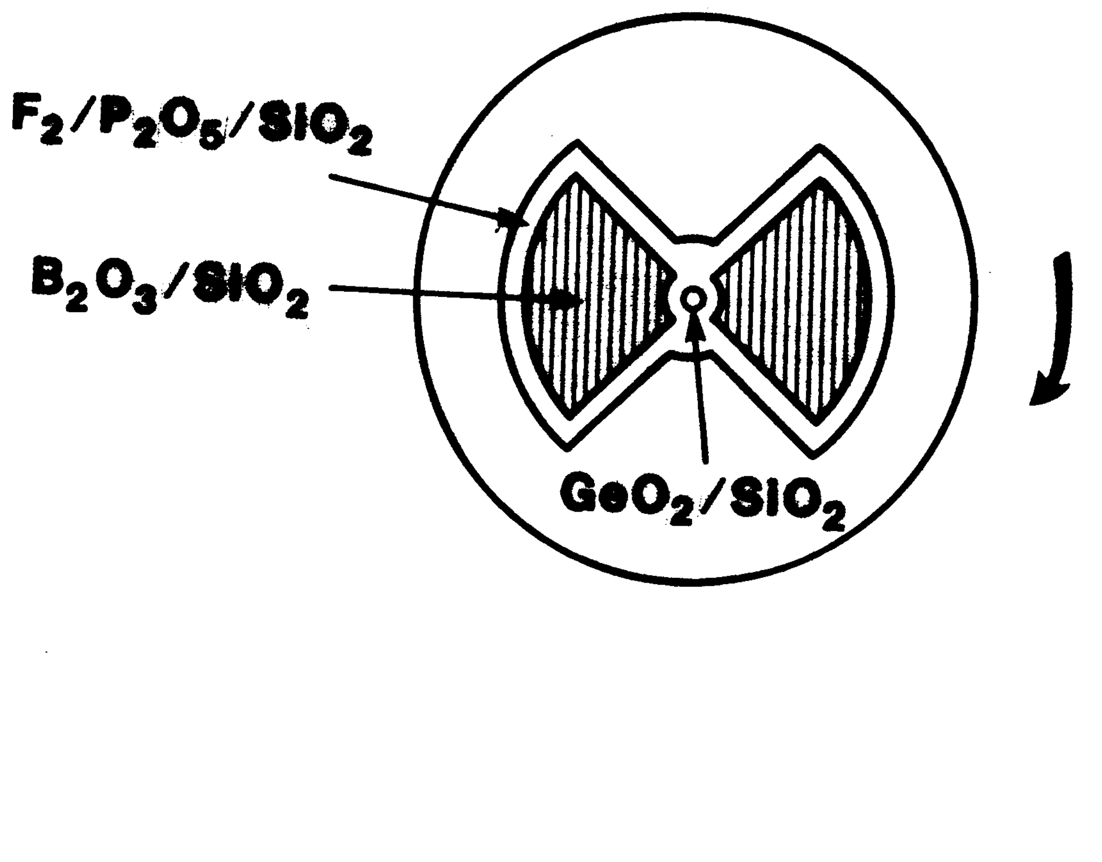


Fig 2(b)

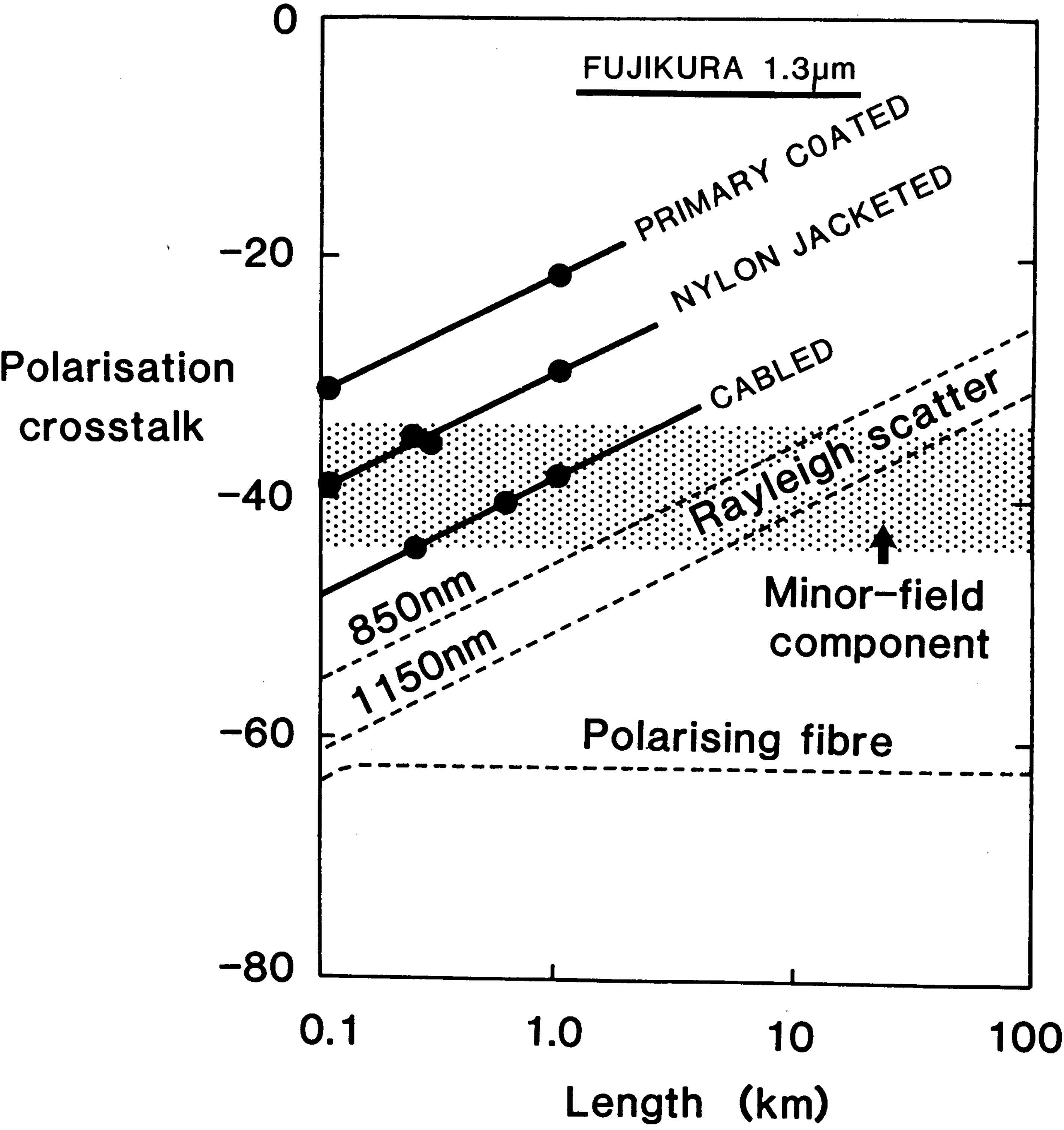


$F_2/P_2O_5/SiO_2$
B_2O_3/SiO_2
GeO_2/SiO_2

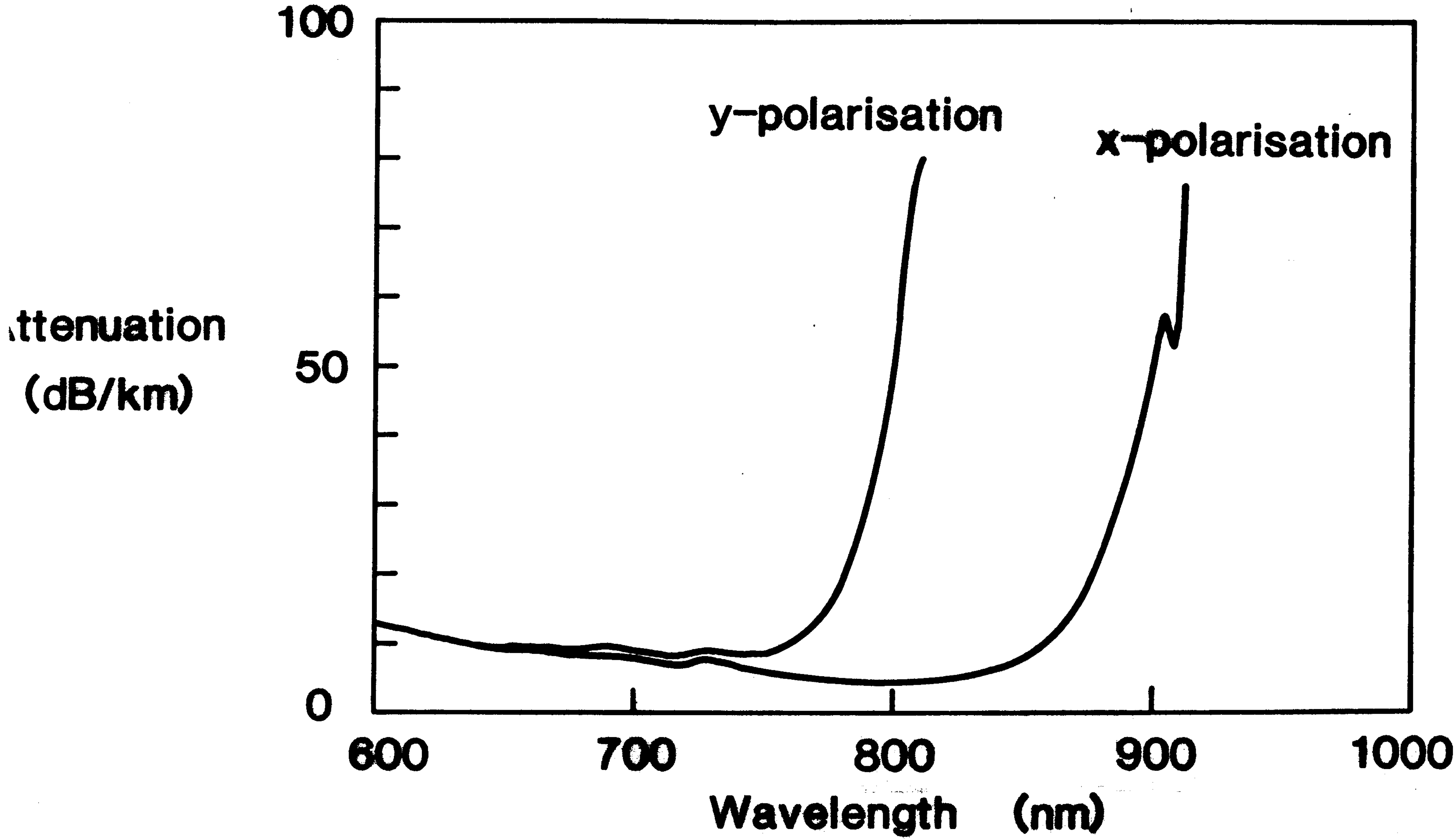


$F_2/P_2O_5/SiO_2$
B_2O_3/SiO_2
GeO_2/SiO_2

Fig 2(d)



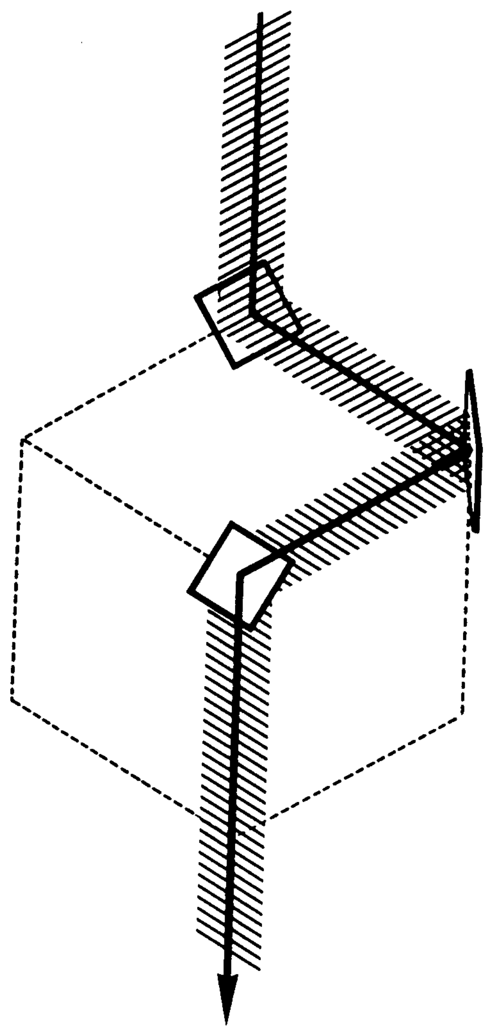
FUJIKURA 1.3μm
PRIMARY COATED
NYLON JACKETED
CABLED
Rayleigh scatter
850nm
1150nm
Minor-field component
Polarising fibre
Polarisation crosstalk
0
-20
-40
-60
-80
0.1
1.0
10
100
Length (km)



ttenuation
(dB/km)
100
50
0
600
700
800
900
1000
Wavelength (nm)
y-polarisation
x-polarisation

Helical core fibre.

Fig 8.5



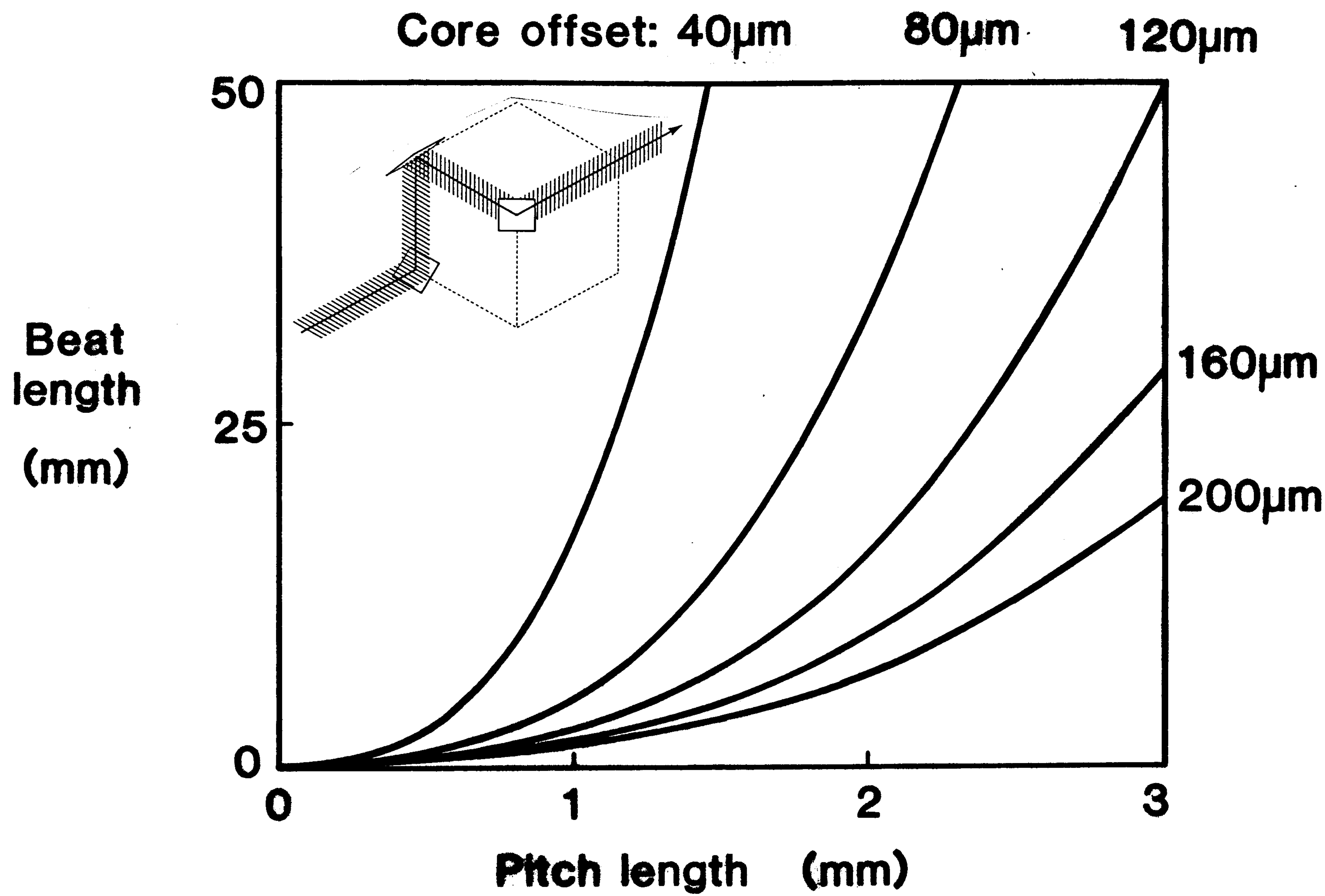
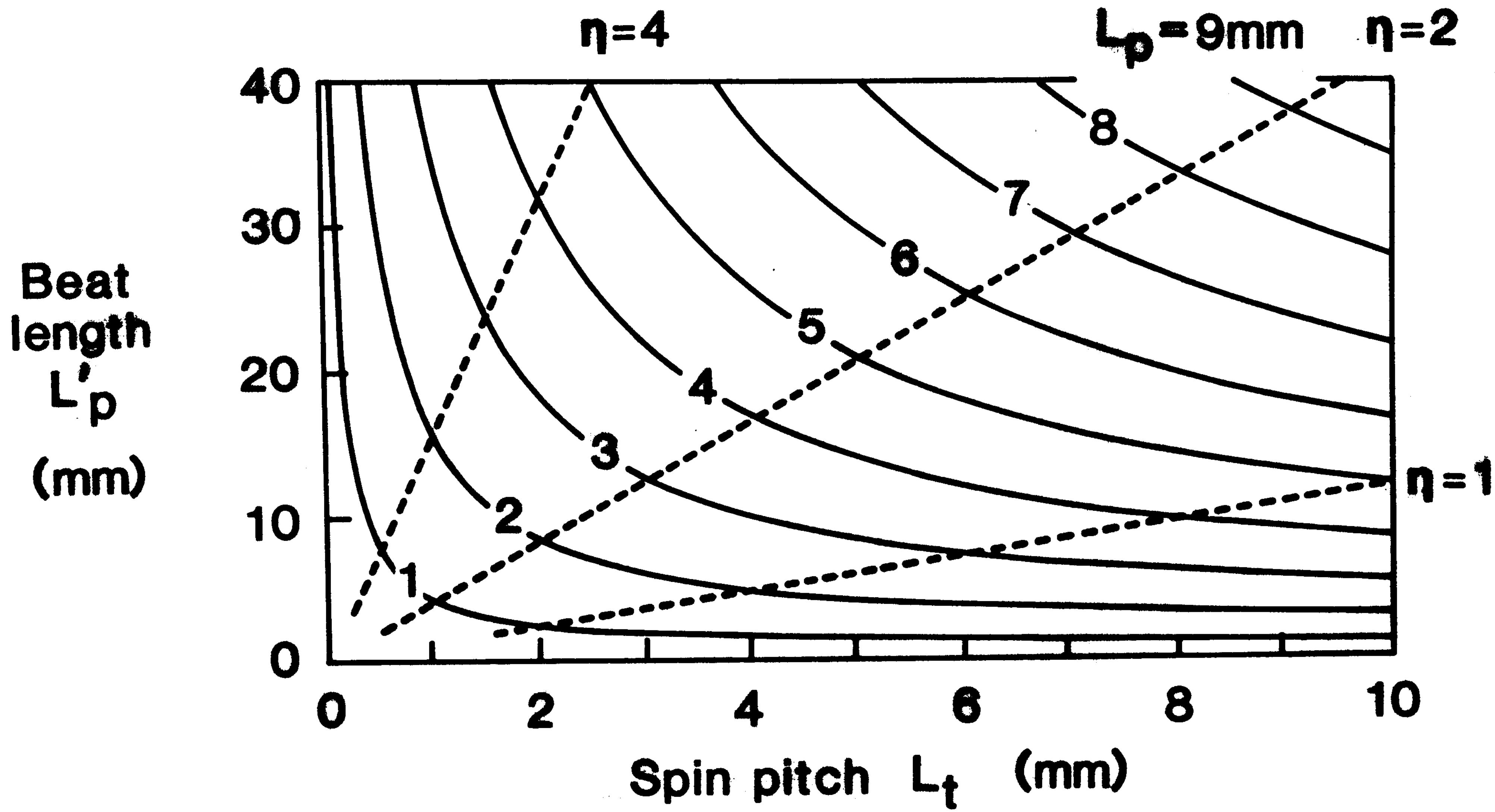

Core offset: 40μm
80μm
120μm
160μm
200μm
Beat length (mm)
50
25
0
0
1
2
3
Pitch length (mm)

Fig 6


η=4
Lp=9mm
η=2
η=1
Beat length L'p (mm)
Spin pitch Lt (mm)
0
10
20
30
40
0
2
4
6
8
10
1
2
3
4
5
6
7
8

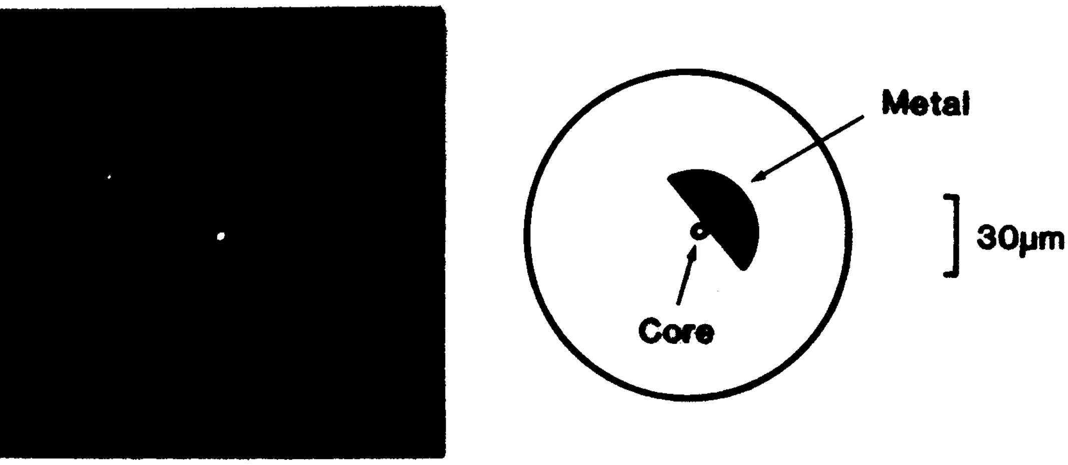
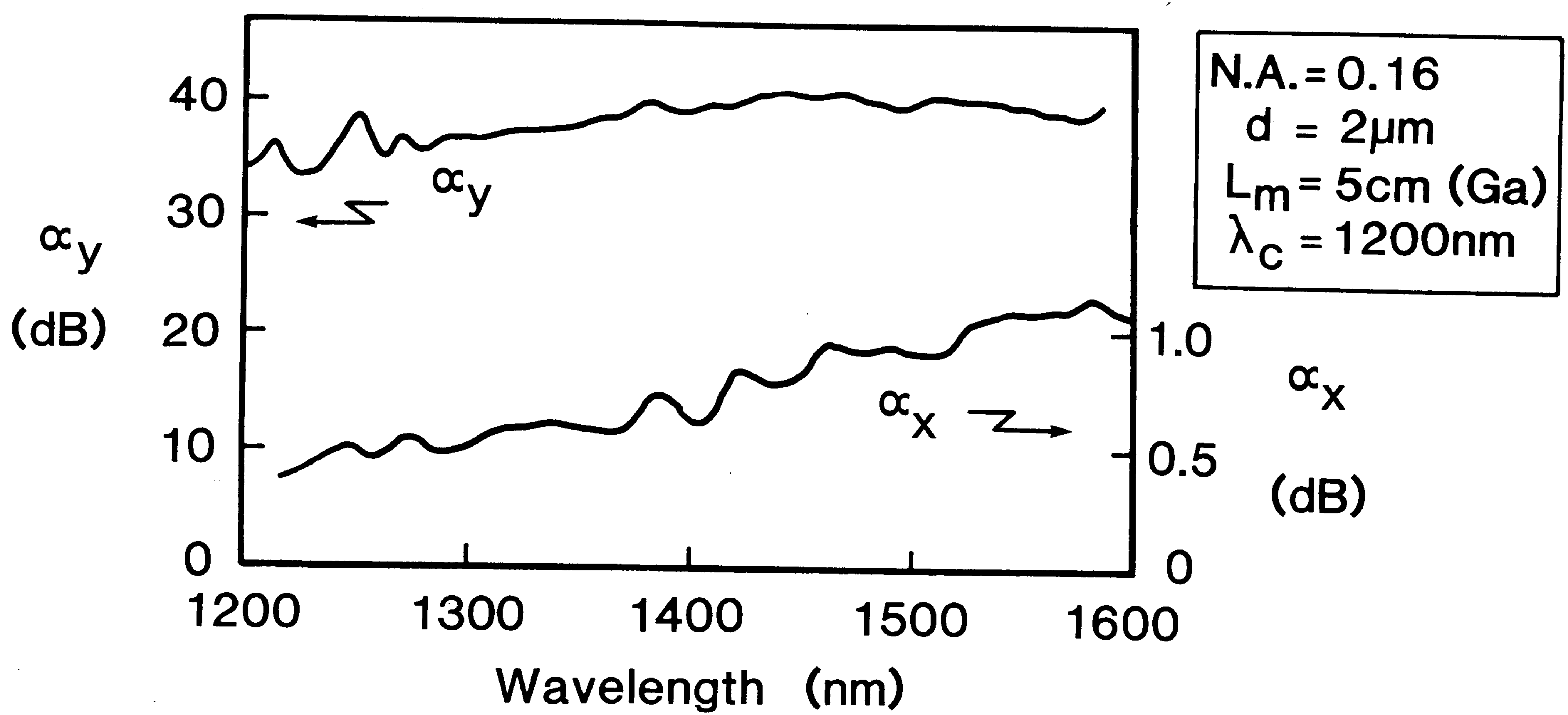


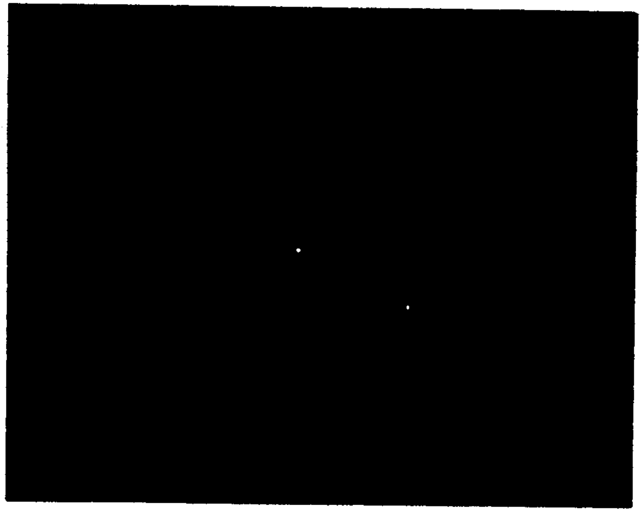
Fig 8.8



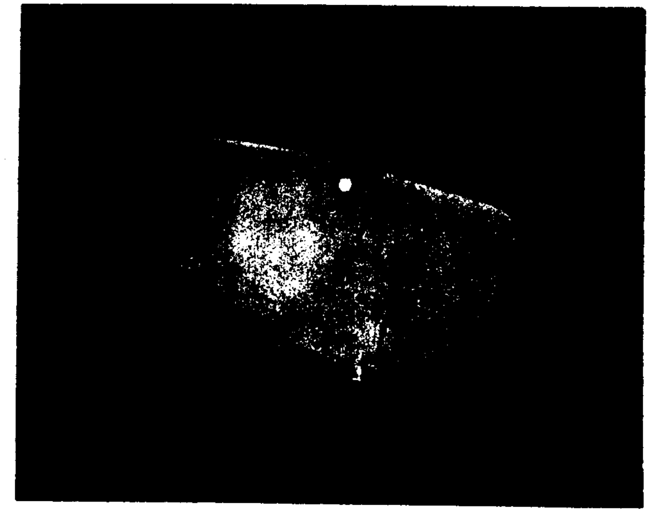
N.A. = 0.16
d = 2μm
Lm = 5cm (Ga)
λc = 1200nm
αy
(dB)
αx
(dB)
40
30
20
10
0
1.0
0.5
0
1200
1300
1400
1500
1600
Wavelength (nm)

12

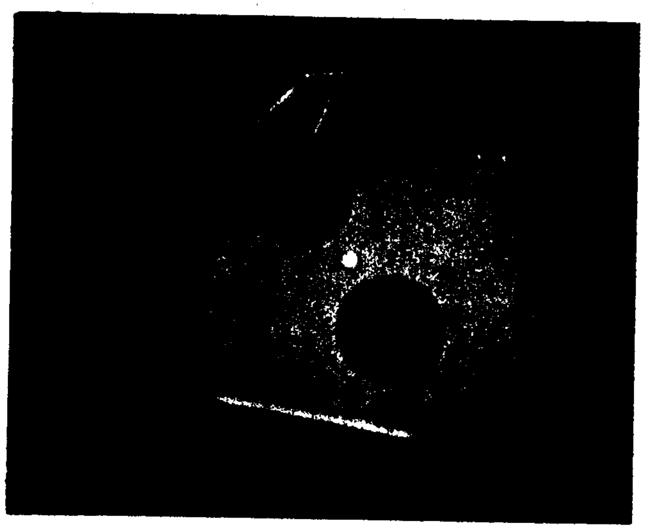
~~COMPOUND GLASS FIBRES~~



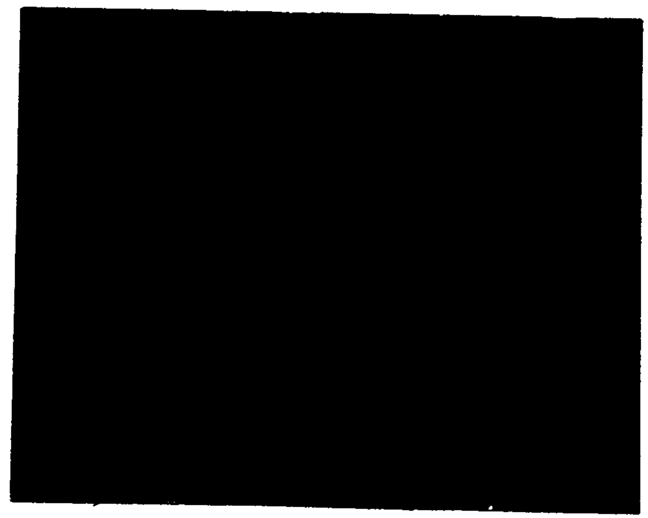
Single mode



D–fibre

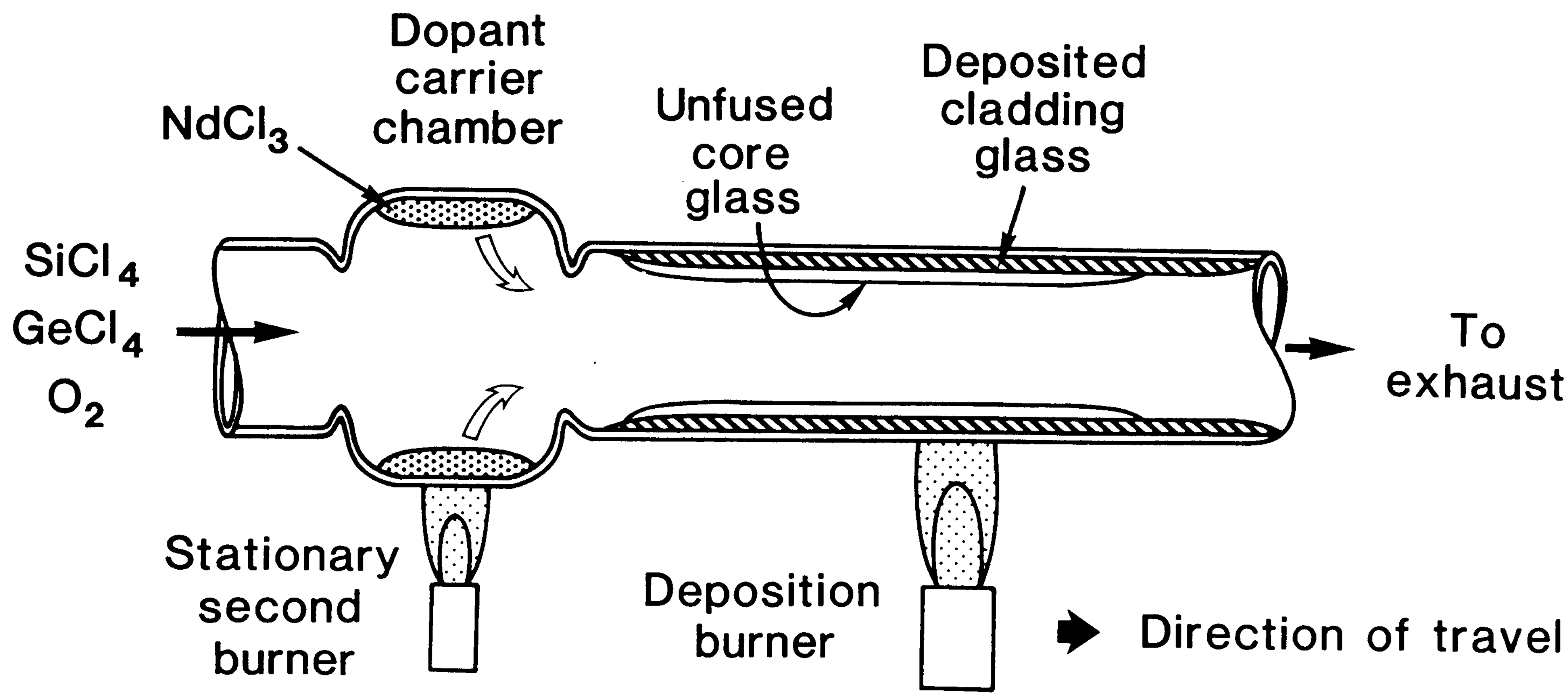


Birefringent fibre

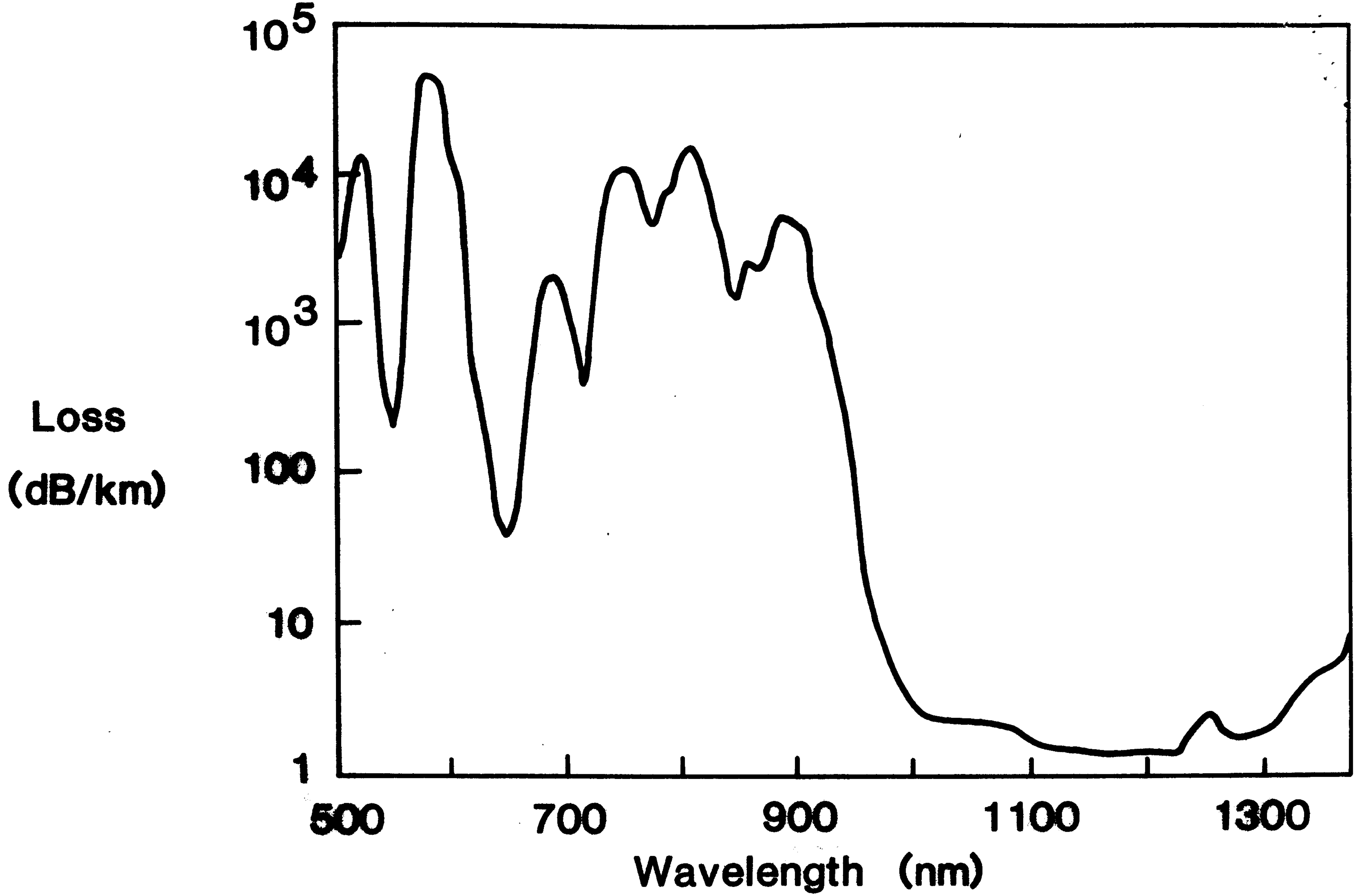


Birefringent–D

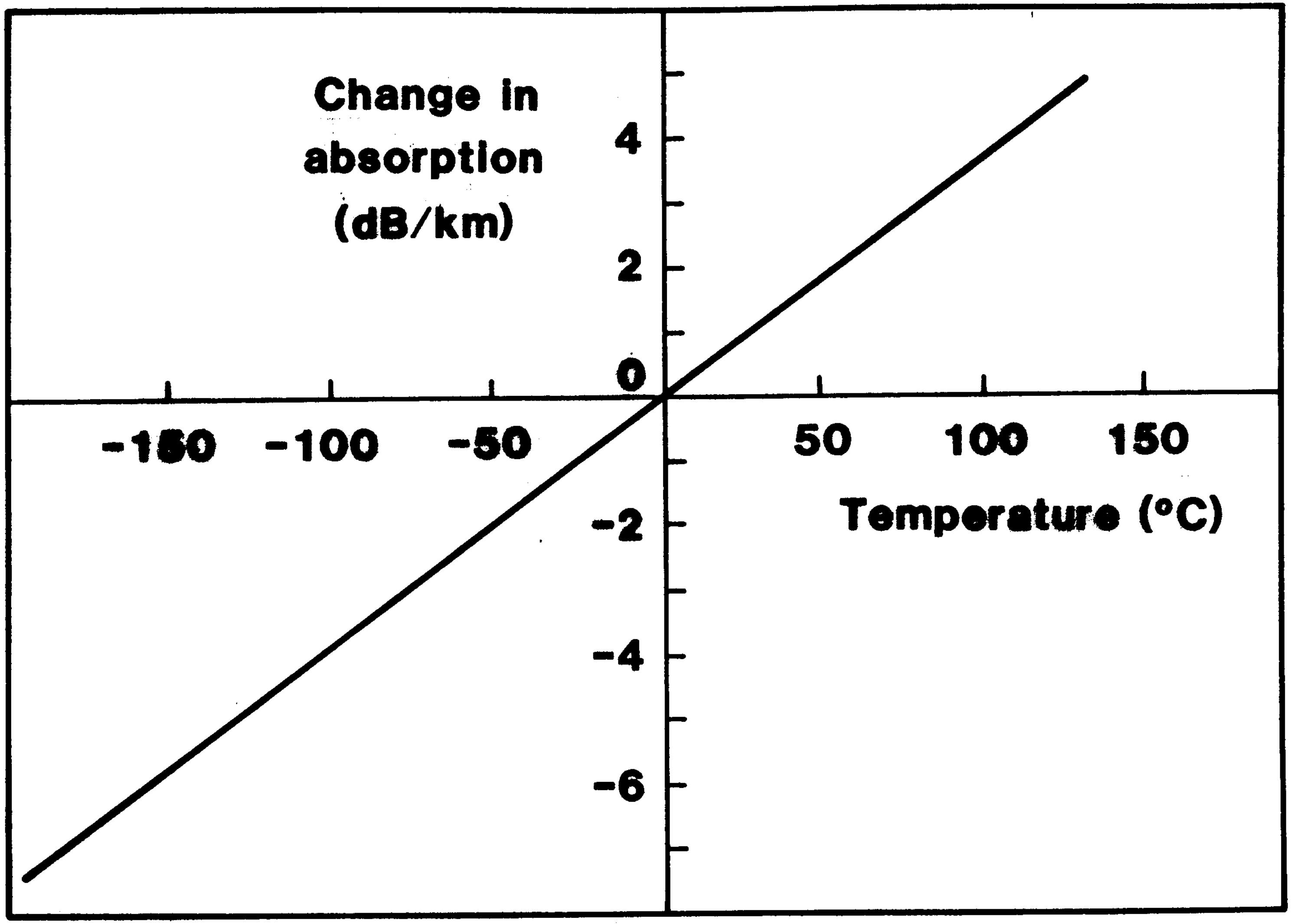
Fg 8 pc

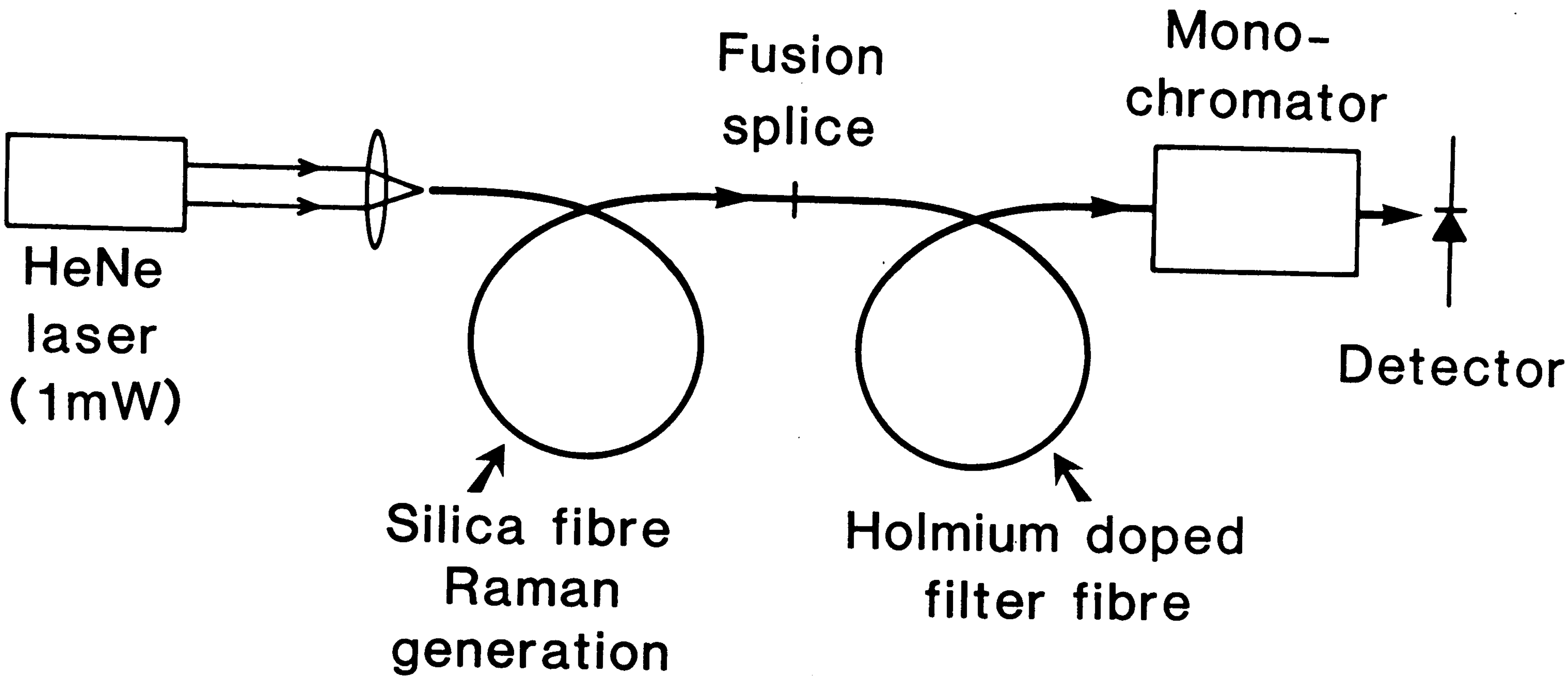


Dopant carrier chamber
NdCl3
SiCl4
GeCl4
O2
Unfused core glass
Deposited cladding glass
To exhaust
Stationary second burner
Deposition burner
Direction of travel

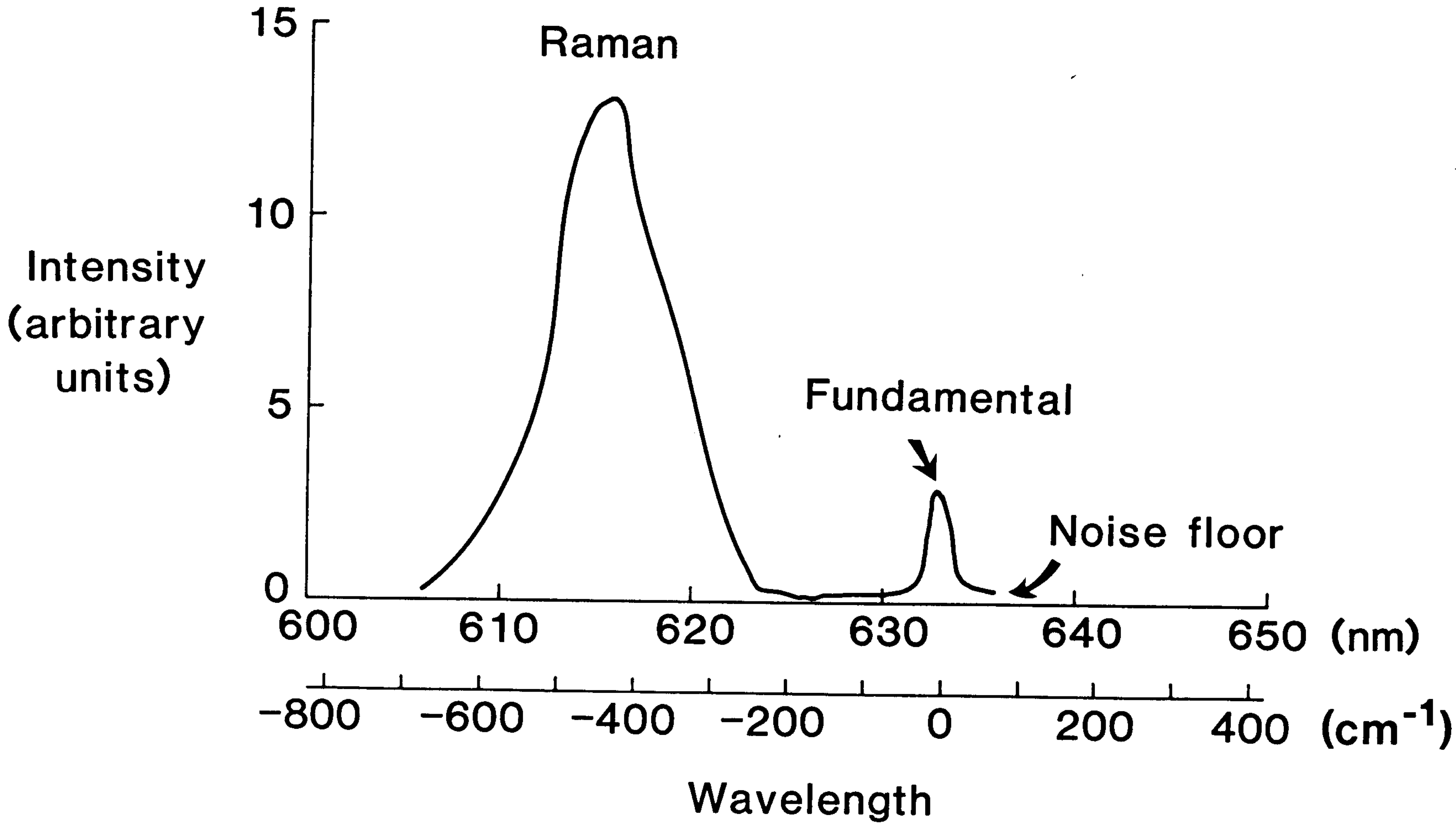


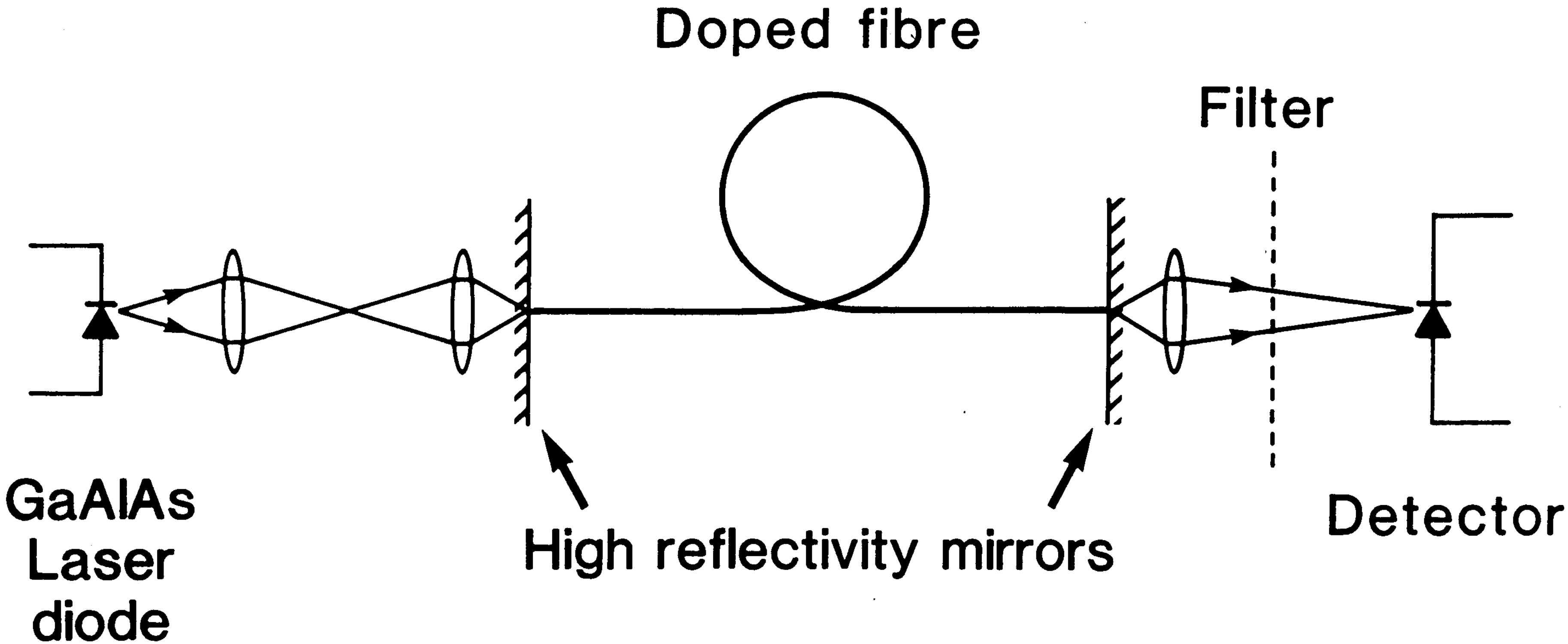
Loss
(dB/km)
10^5
10^4
10^3
100
10
1
500
700
900
1100
1300
Wavelength (nm)


Change in
absorption
(dB/km)
4
2
0
-2
-4
-6
-150
-100
-50
50
100
150
Temperature (°C)



Fusion
splice
Mono-
chromator
HeNe
laser
(1mW)
Detector
Silica fibre
Raman
generation
Holmium doped
filter fibre


Raman
Intensity
(arbitrary
units)
15
10
5
0
Fundamental
Noise floor
600
610
620
630
640
650 (nm)
−800
−600
−400
−200
0
200
400 (cm-1)
Wavelength


Doped fibre
Filter
GaAlAs
Laser
diode
High reflectivity mirrors
Detector

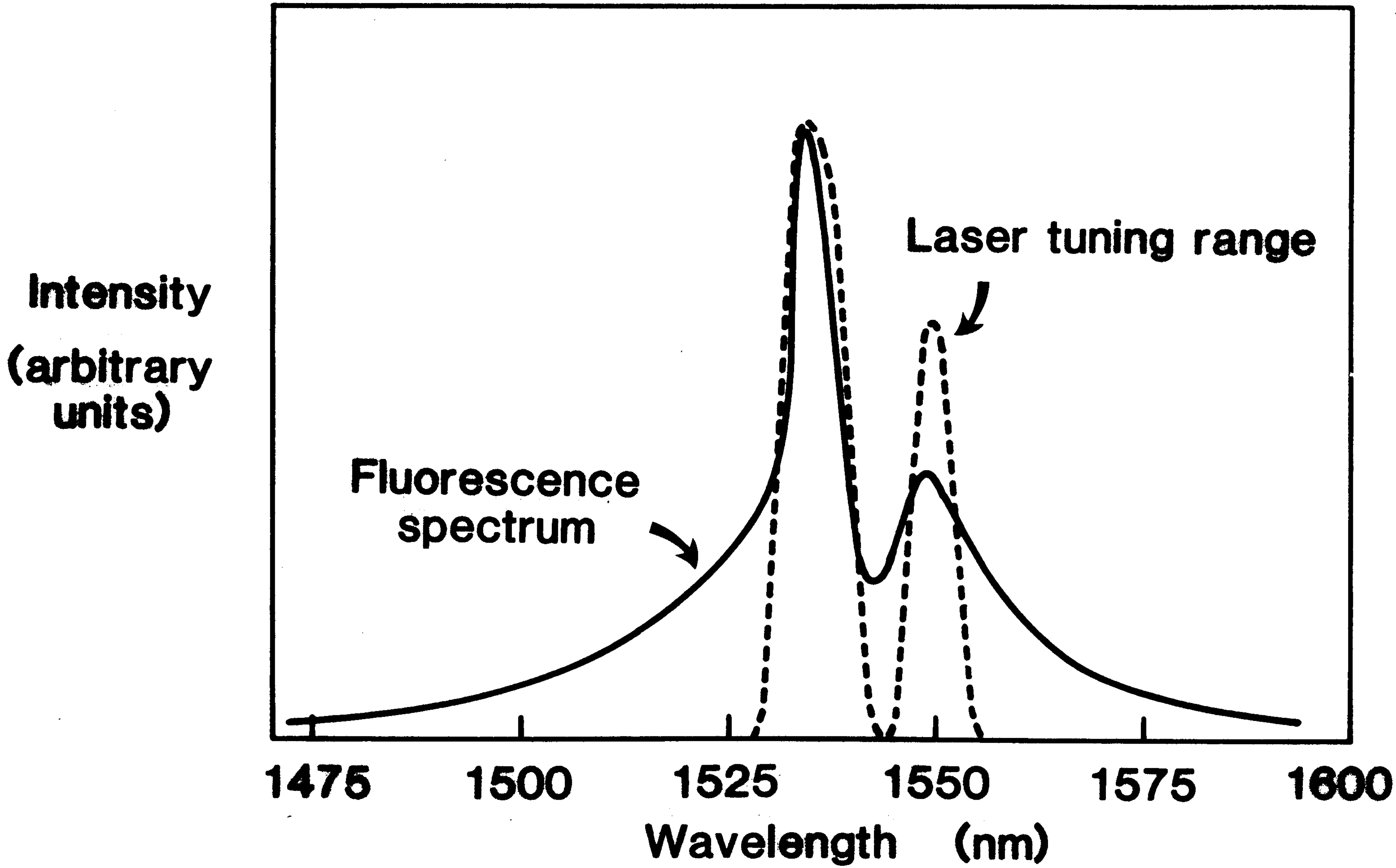

Intensity
(arbitrary
units)
Fluorescence
spectrum
Laser tuning range
1475
1500
1525
1550
1575
1600
Wavelength (nm)

Fig 8.17