NEW FABRICATION TECHNIQUES FOR OPTICAL FIBRE SENSORS AND LASERS

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Abstract

The paper describes the fabriction of optical fibres of various novel designs, developed at the University of Southampton, which can have the properties of nearly zero birefringence, strong linear birefringence, strong circular birefringence or can behave as linear polarisers. A further new technique, also devised at Southampton, allows the incorporation of rare-earth ions into the core of a single-mode fibre. Such fibres have been operated as lasers and sensors. They have provided, for the first time, continuous operation at room temperature when pumped by a semiconductor laser diode, and have been operated as amplifiers and tunable optical sources. Single-pulse generation by Q-switching has also been achieved. Fibre lasers are simple, flexible, do not need accurate optical alignment and are relatively unaffected by environmental conditions.

New Fibres

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. 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.

At Southampton we have been studying four types of structure, involving new materials and new fibre designs. Firstly we have fabricated fibres with zero birefringence[1], strong linear birefringence[2] and strong circular birefringence[3,4]. Secondly we have made fibres with longitudinal metal components close to the core so that the effect of transverse electric fields can be investigated with a view to producing electrically-activated modulation and switching. Thirdly, a technique has been developed for doping the core of single-mode fibres with rare-earth and transition-metal materials through an extension of the MCVD technique[5]. Fourthly we are looking at the fabrication of fibres with non-silica glasses chosen so as to enhance the Kerr, Faraday and acousto-optical effects.

This paper addresses the first and third of these topics.

Fibres with Negligible Birefringence and Polarisation Mode Dispersion

Research into "funny fibres" for sensor applications began at Southampton in 1979 with an attempt to make a single-mode fibre with low birefringence suitable 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 linear birefringence in order to observe the small field-induced polarisation rotation. This is particularly the case in the fibre current monitor 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. 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[6]. 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. 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 100m.

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 next section) of about 10cm and in any case stronglytwisted 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[1] 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 which is not affected by the spun core, so that spun fibres can be used as sensors. They are particularly useful for measurement of magnetic fields and electric currents if the externally-induced birefringence is kept small.

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 used in 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, will 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, will 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[7] 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 means in turn 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[8] 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 by introducing 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[9] but the one producing the largest birefringence is the "Bow-Tie" structure[10] 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 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.

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 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 0.55mm ($B = 10^{-5}$) have been measured

In order to obtain maximum birefringence the stress-producing sectors should approach as close to the core as possble. 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 0.7mm and transmission losses of less than 0.2dB/km have been obtained.

Polarisation-Maintaining Fibres and Polarising 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 will continue to be linearly polarised along the entire length of the fibre. This is 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 then some of the original polarisation will couple into the orthogonal mode and will continue to propagate in that mode to the output.

Another method of operating a Bow-Tie 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.

One method of introducing a preferential loss into one mode is to wind 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 will be at different wavelengths. This effect is illustrated in Figure 2, showing 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[11]. The wavelength region in which polarising action occurs can also be controlled. Extinction ratios of 60dB have been obtained together with extremely wide wavelength windows. For example, polarising fibres wound on drums of 13cm diameter have demonstrated windows from 760nm to 910nm, and 100nm at 1300nm, where the extinction ratio is well beyond the measurement limit of 40dB (Private Communication: York VSOP Ltd.).

Circularly-Birefringent Fibres

It is also possible to produce fibres exhibiting a high degree of circular birefringence. Such fibres can find application in the monitoring of electric current and magnetic fields and also in the control of polarisation in telecommunications. 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-hand, 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 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. Such fibres have been developed and fabricated at Southampton[12,13] 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 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 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 5mm (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 maintaining single-mode operation. The core diameter can thus be much larger than normal. The use of such fibres for measuring magnetic fields and electric currents is now being investigated.

Rare-Earth Doping of Single-Mode Fibres

In order 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. In this way, as is well known, transmission losses have been reduced to a few tenths of a decibel per kilometre. 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-guidance regions of the fibre. Possible developments could be

1. Fibre lasers and amplifiers.

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

3. Increased Verdet constant.

4. Increased Kerr effect and non-linear optical coefficients.

We have devised a method of doping fibres through a modification of the MCVD technique. One of the major advantages 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.

The method adopted to overcome these difficulties[5] is illustrated in Figure 3. 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.

Initial results have been very successful. A number of dopants, such as neodymium, erbium, ytterbium, terbium and praesodymium, have been incorporated into fibres, giving absorption bands of very high loss (greater than 3000dB/km) at visible and near-infra-red wavelength, whilst maintaining the characteristic low loss (less than 2dB/km) in the region of 1.3μm. 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 single-component, or multicomponent, 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 -1.4μm. Such fibres can produce distributed sensors as well as fibre lasers, amplifiers and active components in optical communication systems.

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

Fibre Lasers and Amplifiers

An example of the absorption spectrum of a lasing fibre is shown in Figure 4 for a single-mode fibre with 30ppm of neodymium in the core. The high-loss absorption bands and the low-loss transmission region are clearly seen. Figure 5 gives the fluorescence spectra for three rare-earth dopants showing the possibility of lasing and amplifying action in three very interesting wavelength regions. So far lasing action has been produced with neodymium and erbium by the simple expedient of placing mirrors at the ends of the length of fibre. A lasing threshold as low as 100μW has been observed with a simple diode laser acting as the pump source. One of the mirrors is dichroic allowing good transmission of pump radiation with a high reflectivity of the laser light. Previously reported neodymium fibre lasers have been pulsed or multimode, exhibiting relaxation oscillations, but we have observed CW operation at a power level of a few microwatts. A ring fibre laser has also been constructed with a fibre coupler to transfer pump radiation into and laser radiation out of, the cavity. The output power from one port was 2mW for approximately 20mW of pump power absorbed in the ring and a threshold of a few milliwatts. The slope efficiency of well over 20% is much higher than with conventional neodymium/glass lasers and thermal effects are negligible so that the fibre laser can be operated in the CW mode without cooling.

Tunable radiation has been produced[13] in both neodymium and erbium fibre lasers by replacing one of the mirrors by a diffraction grating. In the neodymium fibre the argon ion pump radiation at 514nm was coupled into the fibre through the plane input mirror. Even without the diffraction grating the gain available is sufficiently high that feedback from the bare endface of the fibre produced lasing action at a pump power of 122mW. With the grating in place threshold was at 25mW, corresponding to 10mW of pump power in the fibre. The laser is tunable over most of the neodymium gain curve producing an impressive tuning range of 80nm.

The erbium fibre laser operates at a wavelength of 1.536μm where the transmission loss of conventional telecommunication fibres is a minimum. Pumping was at 514nm with an argon ion laser. Despite the fact that an erbium laser is a 3-level system the small core diameter of 5μm allows saturation of the absorption to be easily achieved with only a few milliwatts of pump power, giving an unprecedented low threshold of about 4mW of absorbed power. The output power was several tens of microwatts. Tunable operation has been achieved over two ranges of 14nm and 11nm near 1.54μm, with an absorbed pump power of only 90mW.

In addition to the above results optical amplification with high gain has also been achieved and will be reported elsewhere, as well as[14] Q-switched operation at 1.55μm giving 60ns pulses of 2W peak output power at a repetition rate of 200Hz.

Even from these early results it is clear that optical fibre lasers can produce efficient solid-state sources of low threshold power which are compatible with optical fibre devices and circuits. The output can be tuned in wavelength and fibre lasers should be cheap compared with conventional ones and have the additional virtues of being completely flexible in design and operation. For example, they can be wound into a tight coil without affecting laser action and there is no need for accurate optical alignment of the active medium nor of the mirrors. The latter can be simply attached directly to the end of a fibre cleaved in the normal way. Fibre lasers can be operated in the single, fundamental, mode giving a well-controlled Gaussian output beam. The threshold powers are small, because of the strong guiding action of the core, so that lasing action should be possible with materials having weak transitions and which perhaps have not yet exhibited laser action by other techniques. Again because of the small core diameter cooling is very effective, allowing CW operation at room temperature. The fabrication process is simple and flexible so that a wide variety of dopants can be incorporated very efficiently and economically.

Conclusion

It is clear that a wide variety of new optical fibre materials and structures are possible giving rise to many different types of sensor application. Optical-fibre components cannot compete with integrated optical circuits in terms of size, but they are flexible, comparatively simple to fabricate, and are compatible with optical fibre transmission lines, so avoiding the large coupling loss between fibres and planar optical circuits. In addition to passive devices, such as couplers and filters, a wide variety of active components can be devised, ranging from optical amplifiers and tunable sources to devices based on non-linear interactions involving soliton propagation, Raman interaction and the like.

Whilst silica-based fibres can be used for current/ magnetic-field sensing the Verdet constant, and therefore the sensitivity, is low. It is hoped that the new doping technique will enable more sensitive materials to be incorporated. Certainly it offers many exciting possibilities for yielding new types of sensing element.

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Figure Captions

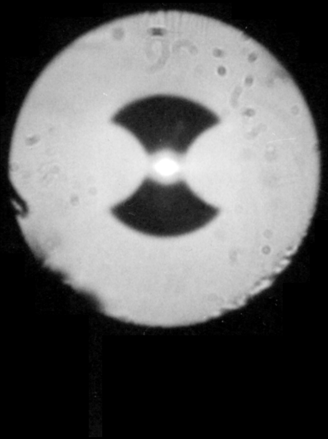
Fig. 1: Cross-section of Bow-Tie fibre showing central core and cladding regions and (dark) stress-producing sectors.

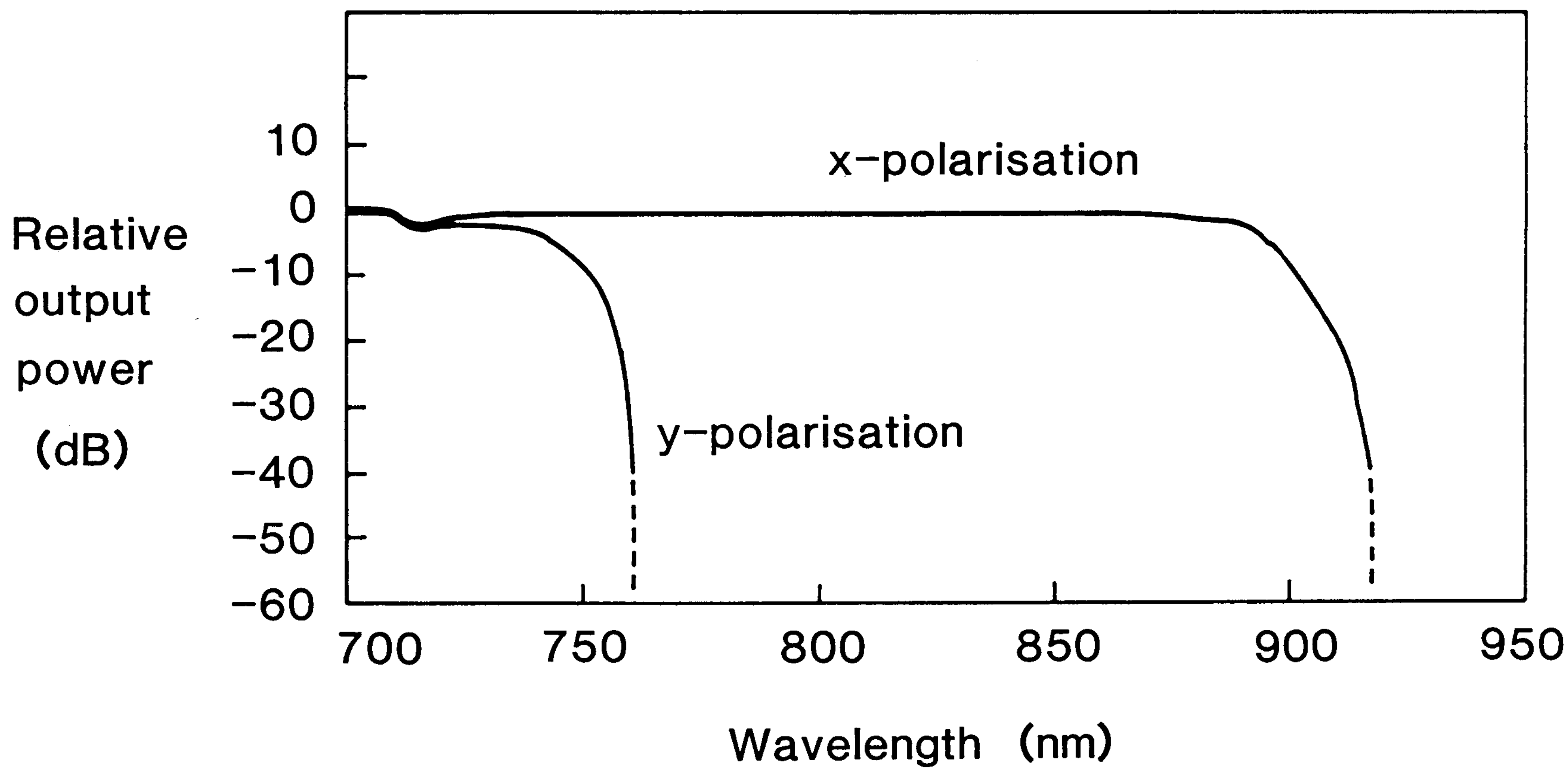
Fig. 2: Transmission losses of the two orthogonally-polarised modes in a 120m length of Bow-Tie fibre on a 13cm diameter drum. The fibre diameter is 95μm. (Courtesy of York VSOP Ltd., Chandler's Ford, Hants).

Fig. 3: Modified deposition tube for rare-earth doping.

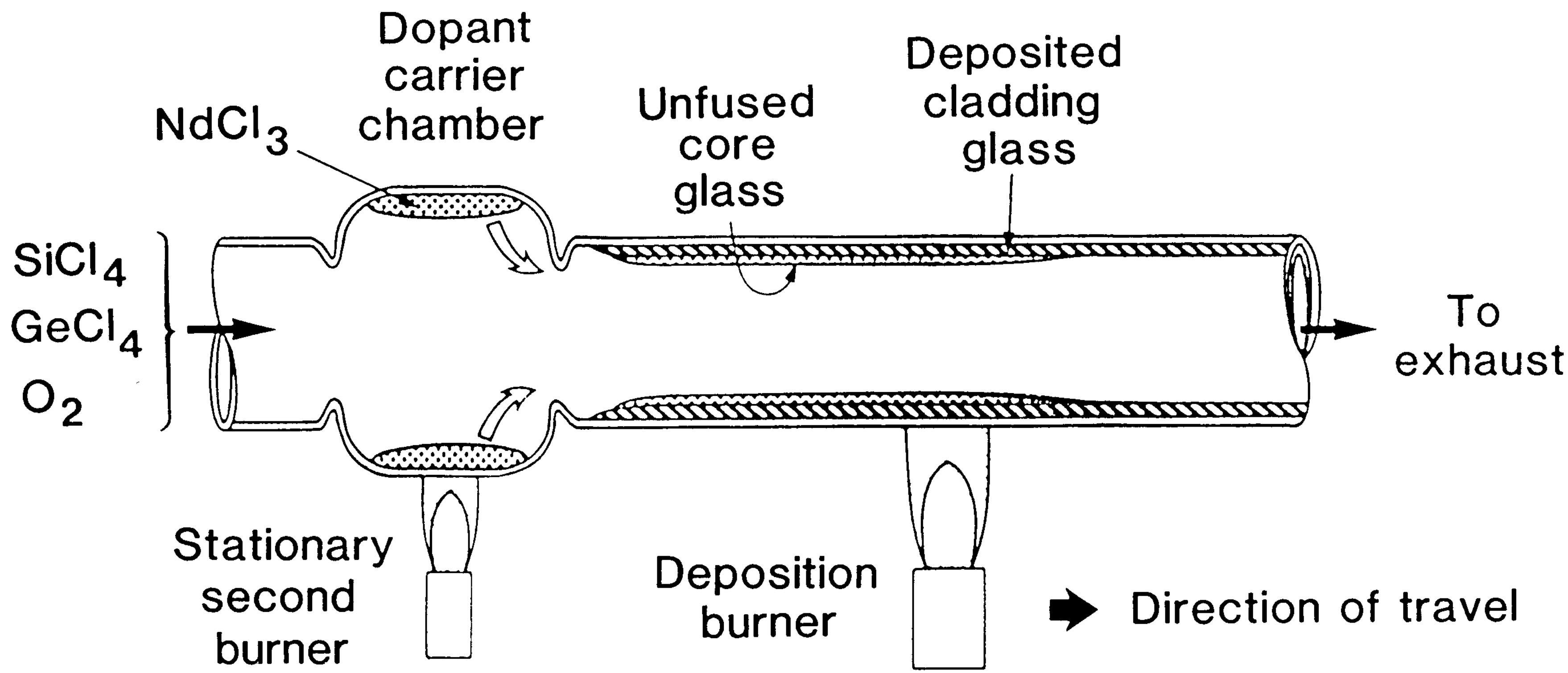
Fig. 4: Absorption spectrum of neodymium fibre laser.

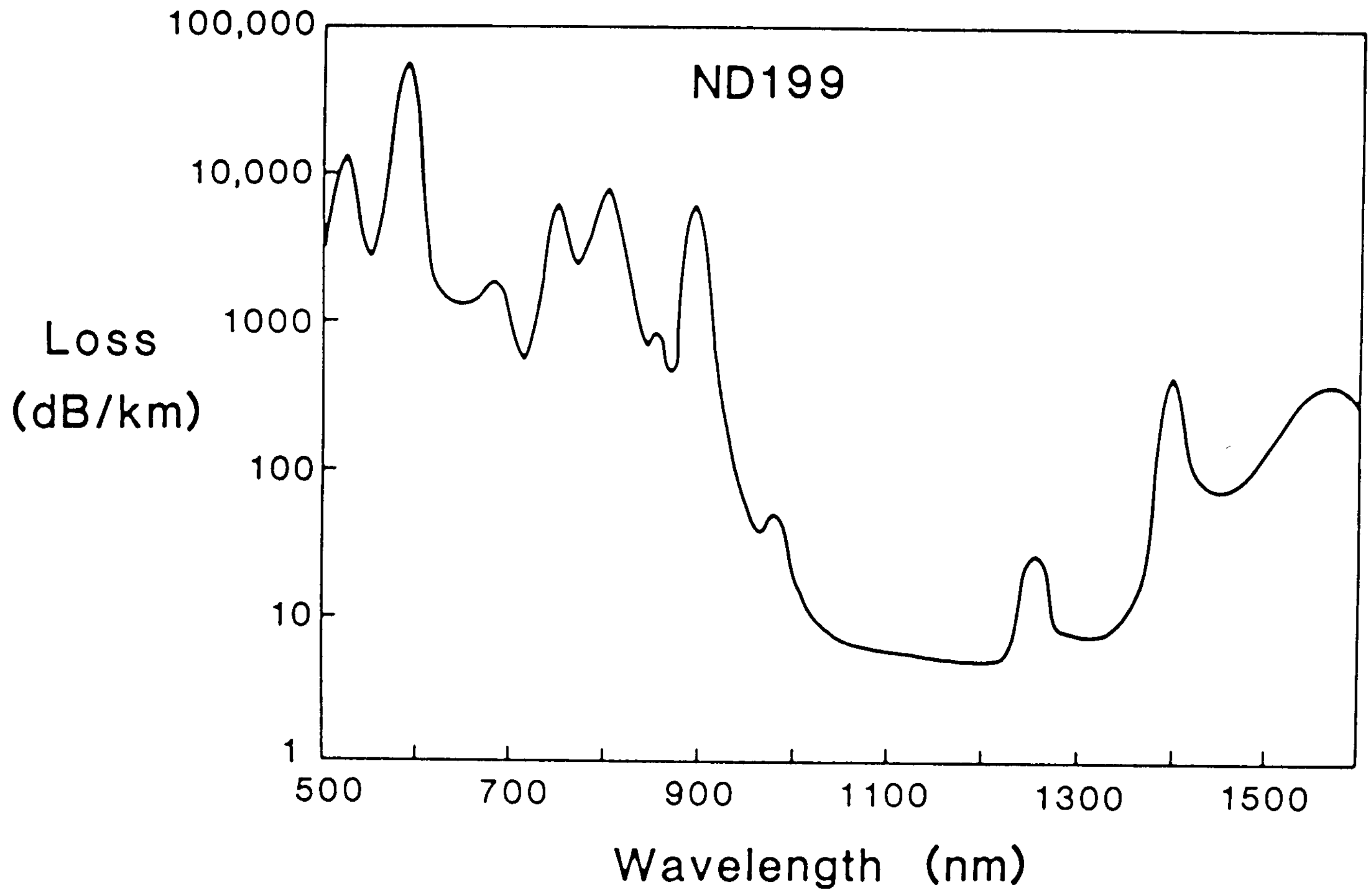
Fig. 5: Fluorescence spectra for fibres doped with terbium, neodymium and erbium.

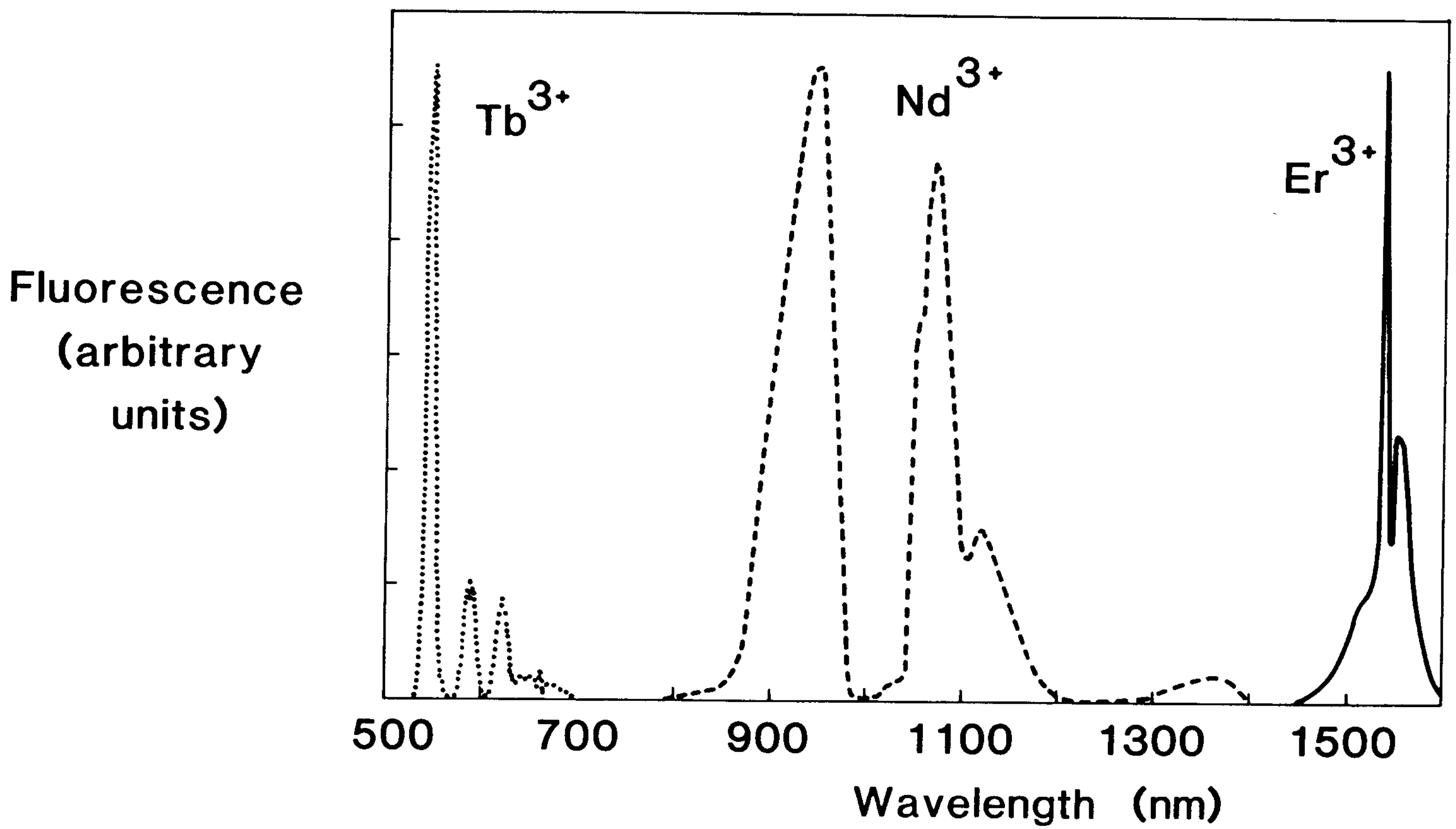




x–polarisation
y–polarisation
Relative output power (dB)
10
0
–10
–20
–30
–40
–50
–60
700
750
800
850
900
950
Wavelength (nm)


Dopant
carrier
chamber
$NdCl_3$
Unfused
core
glass
Deposited
cladding
glass
$SiCl_4$
$GeCl_4$
O_2
To
exhaust
Stationary
second
burner
Deposition
burner
Direction of travel


ND199
Loss
(dB/km)
100,000
10,000
1000
100
10
1
500
700
900
1100
1300
1500
Wavelength (nm)



Fluorescence (arbitrary units)
Tb3+
Nd3+
Er3+
500
700
900
1100
1300
1500
Wavelength (nm)

5