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DESIGN OF SPECIAL FIBRES FOR SENSORS

W.A. Gambling

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 sensors in control and process engineering.

At Southampton[1] we have fabricated fibres with zero birefringence, strong linear birefringence and strong circular birefringence. Secondly we have made fibres with longitudinal metal components close to the core to produce 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.

Linearly-Birefringent Fibres

In many control applications it is necessary that the state of polarisation of the modes in a fibre should be strictly controlled. For example it is necessary to control linear polarisation 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 because both intrinsic imperfections and external factors such as bends, stress and changes of temperature, produce some optical azimuthal inhomogeneity. Thus linearly-polarised input light may be decomposed into linearly-polarised, orthogonal, components along the two principal transverse planes and these components have different phase velocities. Coupling between the two orthogonal components causes 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.

The best 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 but the one producing the largest birefringence is the "Bow-Tie" structure[2] in which the shape of the stress-producing sectors has been optimised to produce the maximum degree of birefringence.

Professor W.A. Gambling is with the Department of Electronics and Computer Science, The University, Southampton, S09 5NH.

The fibres are fabricated by a modification of the MCVD process. A layer of stress-producing material (for example borosilicate glass) is deposited, some of it is etched away on opposite sides of the preform tube and the tube is again rotated and layers of cladding, followed by core, glass are deposited in the usual way. During the collapse process into a solid rod preform cusp-like regions of stress-producing glass in the tube assume the Bow-Tie shape in the fibre. The preform rod is then drawn into a fibre. Cooling from the drawing temperature of approximately 2000°C to room temperature produces a high degree of asymmetric stress due to the different thermal expansion coefficients of the borosilicate sectors and the silica substrate.

The degree of birefringence can be assessed easily by looking at the light scattered sideways from the fibre. The two propagating modes run into, and out of, phase at a rate depending on the birefringence so that the scattered light varies periodically in intensity. Beat lengths of less than 1mm (modal birefringence $B = 6x10^{-4}$) can be obtained.

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 equal attenuation. If the same power is launched into each of the modes then, because of the different phase constants, 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 providing no mode conversion occurs the light will continue to be linearly polarised along the entire length of the fibre. 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. Thus 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. The wavelength region in which polarising action occurs can also be controlled. Extinction ratios of 40dB have been obtained.

Another method is by introducing a longitudinal metal surface close to (within about 2µm), and parallel with, the core. One of the modes is then heavily attenuated compared with the other.

Short lengths of such metal/glass composite fibres can have extinction ratios exceeding 50dB.

Fibres with Negligible Birefringence

Fibres with almost zero internal birefringence[3] can be made by rotating the preform of a conventional fibre about its longitudinal axis 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 with the result 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 by exploiting the Faraday effect. Thus the angle of polarisation is rotated by an amount proportional to the integral of the magnetic field strength along the length of the fibre.

Circularly-Birefringent Fibres

It is also possible to produce fibres exhibiting a high degree of circular birefringence. Such fibres also can find application in the monitoring of electric current and magnetic fields.

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 the fibre will break at beat lengths shorter than about 10cm. Also, of course, a fibre twisted in this way is difficult to handle experimentally.

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[4] 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 $B = 1.3\times10^{-4}$) and less have been produced.

Rare-Earth Doping of Single-Mode Fibres

Optical fibres 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. Initial results have been very successful. A number of dopants, such as neodymium, erbium and terbium, 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. 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. 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 2dB/km for a 50°C change in temperature. In further work a silica fibre doped with holmium has been fabricated and has a temperature resolution of better than 1°C and a spatial resolution of 3m over a temperature range of -200°C to 100°C.

Conclusions

New types of material and structure for optical fibre are emerging which present interesting possibilities for sensing and control. The next few years will see many advances and improvements in fibre properties.

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