ANALYSIS, FABRICATION AND PROPERTIES OF SINGLE-MODE FIBRES EXHIBITING EXTREMELY LOW POLARIZATION BIREFRINGENCE

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Introduction

There is currently a great deal of interest in the development of single-mode fibres, capable of transmitting linearly-polarized light[1-3]. Conventional monomode fibres exhibit linear birefringence[1]; they therefore have an output state which is, in general, elliptically polarized and different from that at the input. Apart from the possible curtailment of the transmission bandwidth caused by this birefringence[4], the indeterminacy of the output polarization is a considerable disadvantage when coupling fibres to polarization-sensitive integrated-optics receivers. In addition, several interesting devices which utilise single-mode fibres have recently emerged and it has been found that the intrinsic retardance present in the fibres accompanied by the uncertainty in output polarization imposes a limitation on performance. Amongst these, the best known are the Faraday-effect current transducer[5], the fibre Raman laser[6] and the fibre gyroscope[7].

Two approaches may be taken to alleviate the problem, the choice of which depends on the application. The first[2,3] and most extensively investigated deliberately enhances the birefringence in the fibre in order to create a preferred polarization axis for propagation; the fibre then requires orientation to both the source and receiver. The solution most appropriate for the Faraday-effect current transducer is to reduce the birefringence to a level at which it becomes insignificant. In this paper we describe a systematic investigation to determine the degree to which this is possible.

A new theoretical analysis is presented which indicates that the required tolerance on core geometry is not as severe as had been previously thought; furthermore we show that by careful attention to fabrication techniques, fibres with a very high degree of circularity and low residual stress levels are possible, resulting in fibres with remarkably low birefringence. The relative effects of core ellipticity and stress are illustrated by means of three fibres exhibiting progressively improved polarization characteristics. The implications for bandwidth limitation in communications systems are also evaluated and it is shown that stress-induced pulse-spreading may represent an absolute limit on the bandwidth in monomode fibres.

Theory

The birefringence exhibited by single-mode fibres is a result of a difference $\delta\beta$ between the two orthogonally polarized states of the fundamental mode. The difference in phase velocities causes the fibre to exhibit a linear retardation, leading to a polarization state which varies periodically along the fibre with periodicity $L = 2\pi/\delta\beta$. Typical fibres have a period of a few cm[1]. The origins of the birefringence are two-fold:

1) An ellipticity in the fibre core establishes fast and slow axes of propagation and produces a retardance which depends on the degree of ellipticity.
2) The presence of an asymmetrical residual stress distribution within the fibre results in stress birefringence and similarly contributes to the observed retardation.

The fabrication of low-birefringence fibres requires a reduction in both core stress levels and ellipticity. We have calculated the effect of the latter using a theory involving Mathieu functions derived from an exact analysis of elliptical dielectric waveguides. The results (fig.1) show the retardation $\delta\beta$ produced by a given deviation from circularity for various values of core/cladding index difference. It may be seen that the tolerance on circularity can be relaxed by choosing a small index-difference (and, by inference , a large core).

For the current transducer a retardation of around 3°/m is required (a periodicity L of ~120m). From the curves this corresponds to a deviation from circularity of no greater than 0.1% for a fibre having an index difference of 3×10^{-3}, a geometrical perfection which has hitherto been difficult to achieve. Note, however, that previous analyses[2] indicate that a considerably higher circularity is required.

Results

A series of fibres was fabricated to investigate the relative effects of core circularity and residual stress on birefringence. The characteristics of three of these are given in the table below.

Fibre No.	VD214	SV 1	GSB 2
Core composition	SiO_2	SiO_2	GeO_2/SiO_2
Core diameter µm	8.5	9.0	4.0
Cladding composition	B_2O_3/SiO_2	Vycor	B_2O_3/SiO_2
Cladding diameter µm	36	-	16.5
Substrate tube	Silica	Vycor	Silica
Overall fibre diameter µm	140	140	85
Relative index difference Δ	7.6×10^{-4}	7.4×10^{-4}	3.4×10^{-3}
V-value at 633nm	2.4	2.5	2.4

All fibres were coated with silicone resin having a thickness of approximately 50µm.

Fibre No. VD214: The fibre was made by chemical-vapour deposition of B_2O_3-doped SiO_2 within a precision-bore silica tube, followed by deposition of pure silica to form the core. A low index-difference was chosen to relax the requirement on core circularity. The deviation from circularity was determined to be less than 1% by etching the fibre end in hydrofluoric acid and examining it under a high-power optical microscope. From fig.1, this level of ellipticity is expected to produce a linear retardation of less than 2.4°/m.

The birefringence measurements on a straight section of the fibre are shown in fig.4. The specific retardance was found to be 126°/m, a figure considerably in excess of that calculated. It would seem, therefore, that stress-birefringence in the fibre has a major effect on the retardation, a conclusion similar to that drawn in reference 3.

Fibre No. SV1: Vycor glass has an expansion coefficient close to that of silica, but has a somewhat lower refractive index. These characteristics may be utilised to produce a fibre with low residual stress level. Using silica rod and a Vycor tube, a fibre was fabricated having the characteristics shown in the table. Again the ellipticity was better than 1%, indicating an expected retardance of 2.2°/m. From the experimentallydetermined retardation shown in fig.4, it may be inferred that the reduced stress level has resulted in an improved value of 66°/m. However, an order of magnitude discrepancy still exists between the experimental value and that calculated on the basis of core ellipticity.

Fibre No. GSB 2: The radial, tangential and axial components of stress within a fibre core are invariant with radial position and depend on the ratio of core to cladding diameter. The transverse values in the cladding differ from those in the core and, furthermore, have a radial variation. A reduction in core stress levels may be achieved by choosing the thermal expansion coefficients of the deposited core and cladding to be equal. In this case, core and cladding are indistinguishable from a mechanical point of view and have equal stress levels. Furthermore, the tensile forces are now distributed over the total area of deposited glass, resulting in a reduction in the core stress level.

A B_2O_3/SiO_2 cladding and a GeO_2/SiO_2 core having matched expansion coefficients were deposited within a silica tube to produce a preform, the cross-section of which is shown in fig.2. The index difference Δ was chosen to be 3.4×10^{-3}, a value higher than in the previous fibres, in order to allow realistic doping levels. Fig.1 indicates that for this Δ an ellipticity of better than 0.06% is necessary to achieve a retardance of 3°/m. Despite this, measurement of the birefringence properties of the fibre (x-section in fig.3) drawn from the preform exhibited remarkably low values of retardance, a value of only 2.6°/m being found (a period length of 140m).

Conclusions

We have shown that it is possible to produce single-mode fibres with the calculated degree of circularity required for low retardation. Moreover, with careful control of residual stress levels fibres with extremely low birefringence are attainable. The retardation achieved (2.6°/m) is the lowest yet reported and suits the fibre ideally for current measuring instrumentation. One of the fibres is presently being used in a prototype current transducer and is undergoing tests on the effect of pressure, vibration and temperature. Initial results are very favourable and indicate that the fibre characteristics make such a device a practical reality.

The implicationsof the present work for telecommunications systems using monomode fibres are also significant. The pulse spreading due to departure from circularity of the fibre core are confirmed by the present theory to be negligible[4] - typically less than 0.1ps/km for $\Delta \approx 10^{-3}$ and ellipticity of 1%. However,the work reported here indicates that the transit-time difference between the two polarisations of the fundamental mode as a result of asymmetrical stress distributions may be far from negligible. For example, for a fibre with a periodicity of a few cm the inferred pulse-spreading may be as large as 50ps/km. The advent of ultra-low loss monomode fibres and consequently long lengths between repeaters means that the ultimate limitation on bandwidth may come from this stress-induced pulse-spreading.

References

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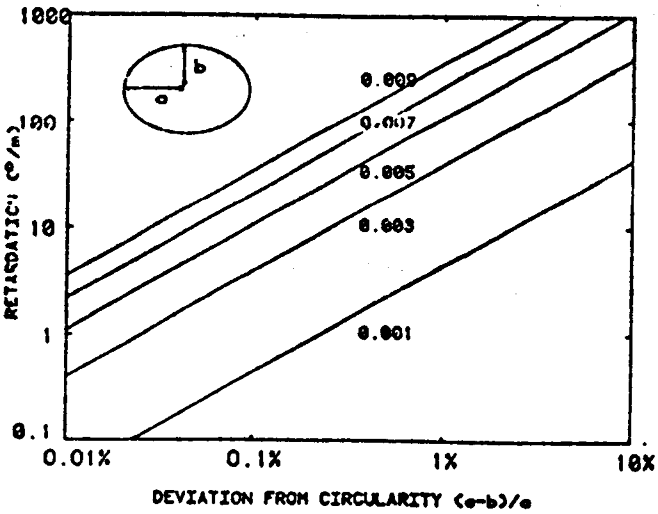

Fig.1 Retardation vs. core circularity in fibre having V = 2.4 at 633nm. Curves are for various values of relative index-difference.

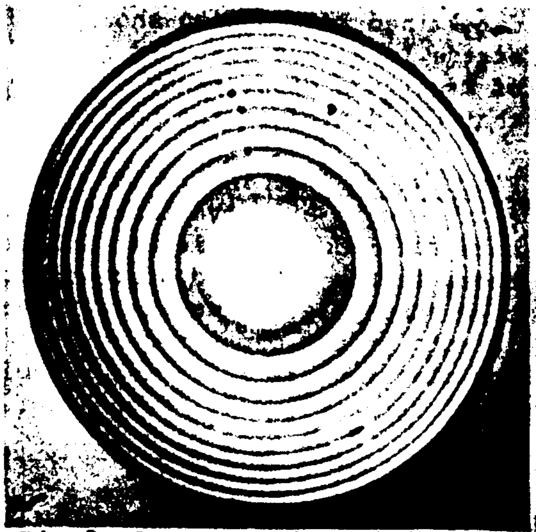

Fig.2 Cross-section of deposited region of GSB 2 preform. The rings are B_2O_3/SiO_2 layers and the central bright region the GeO_2/Si core.

Fig.3 Cross-section of fibre produced from preform of Fig.2.

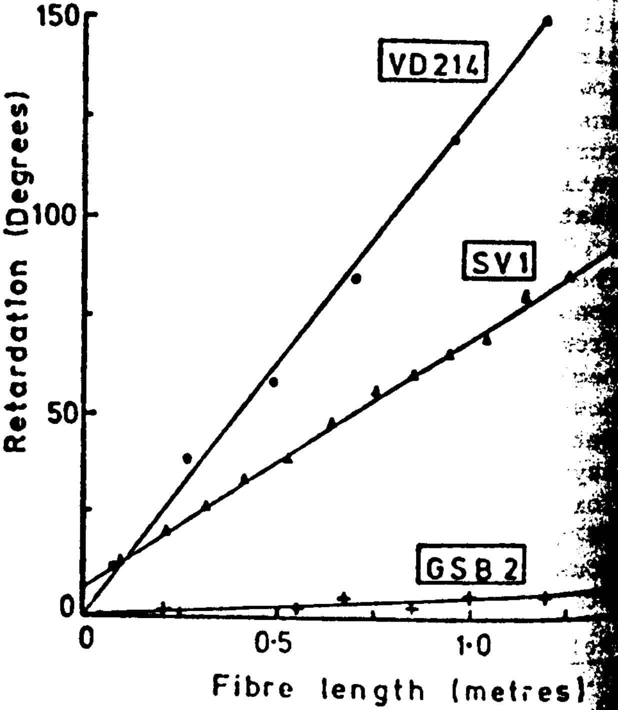

Fig.4 Phase retardation of fibres sh
Specific retardance values ar
VD 214 : 126°/m
SV 1 : 66°/m
GSB 2 : 2.6°/m

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