# FUNDAMENTAL LIMITS TO THE TRANSMISSION OF LINEARLY POLARISED LIGHT BY BIREFRINGENT OPTICAL FIBRES

*Indexing terms: Optical fibres, Optical transmission, Birefringence*

Experimental results are presented which show that the fundamental mode in highly birefringent fibres is not plane-polarised, as is normally assumed, but has significant orthogonal field components. These components limit the maximum measurable polarisation intensity extinction ratio to $\sim 40$ dB. Implications for polarisation measurements and fibre gyros are outlined.

*Introduction:* It is well known that the fundamental mode in an optical fibre waveguide consists, in fact, of two orthogonally polarised modes whose propagation constant spacing is equal to the birefringence.[1] Using the approximation of weak guidance,[2] these modes can be considered plane-polarised.[3] For conventional monomode fibres with low birefringence we have calculated that this approximation is valid to $\sim 70$ dB, i.e. that the residual (or minor) orthogonally polarised components of the plane-polarised mode are present at this intensity level.

To date the approximation has also been assumed to be sufficient to describe propagation in highly stress-birefringent fibres where the core is anisotropic and the propagation constant spacing is large. This implicit assumption is important in the fibre gyroscope where polarisers and fibre components having polarisation extinction ratios greater than 120 dB may be required,[4] and in measurements of fibre polarisation-holding ability.[5] In the latter the degree of induced coupling between polarised modes (the $h$-parameter[5]) is measured using a linear polariser as a mode selector at the output of the fibre, thus assuming that the mode is plane-polarised. The purpose of this letter is to show that, for present-day applications, the assumption of plane-polarisation is grossly inadequate to describe the mode-polarisation properties, particularly for birefringent fibres.

*Experimental:* The field directions of the fundamental $y$-polarised $HE_{11}$ mode of the fibre is shown in Fig. 1$a$ with curvature exaggerated. Figs. 1$b$ and $c$ show the mode decomposed into its major $y$-polarised and minor $x$-polarised field components, as would be seen if the mode were analysed with

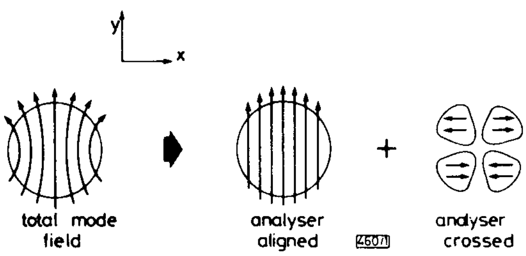


**Fig. 1** *Decomposition of $y$-polarised mode into major $y$ and minor $x$ plane-polarised components*

an aligned and crossed polariser. The assumption of weak guidance and plane polarisation requires the latter four-spot pattern to be present at a negligible level. Our calculations show that for a typical telecommunications-grade fibre this is indeed the case, the minor field power being $\sim 70$ dB relative to the power contained in the major field. The value we have measured ($-60$ dB), while limited by the polarisers available, is consistent with this Figure.

The magnitude of the minor field component was determined in various highly birefringent bow-tie[6] and elliptical-jacket[7] fibres by exciting one polarised mode with a film or prism polariser and observing the far-field output through a crossed analyser. The fibres were $\sim 1$ m in length and kept as straight as possible to avoid mode coupling. The presence of only one fibre mode was further confirmed by gently heating the fibre to change the relative phases between polarised modes. If the unwanted mode was present to any degree, the four-spot output pattern was seen to change periodically.

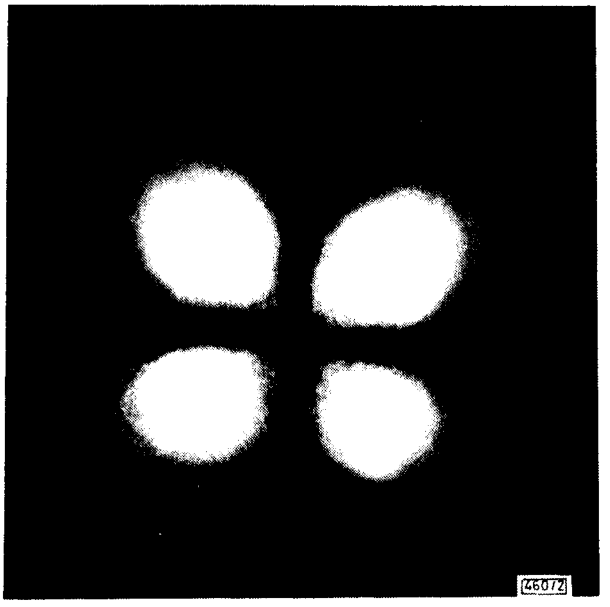


**Fig. 2** *Far-field pattern of minor field components as seen through a crossed polariser at 633 nm*

Fibre is a bow-tie design with index-matched sectors; birefringence $B = 3 \times 10^{-4}$ and $V = 2.2$

In all highly birefringent fibres (B around $3 \times 10^{-4}$) the minor field component was found to be present at power levels between $-45$ and $-38$ dB, which is two or three orders of magnitude higher than in conventional monomode fibres. A typical far-field pattern of the minor field component in a bow-tie fibre is shown in Fig. 2, and was measured to be 39 dB lower in intensity than the major field component. A similar pattern was also observed in the near field by colimating the fibre output through a prism polariser with a stress-free microscope objective, thus confirming that the observed pattern was not the result of passing a diverging beam (i.e. the far field) through the polariser. As expected, fibres with lower birefringence approached the figure measured for a conventional fibre ($-60$ dB).

*Implications:*

*Polarisation measurements:* To our knowledge, no reports have ever been made of extinction ratios measured higher than 45 dB, even in short lengths of high-birefringence fibres where mode coupling is low. An obvious implication is that the measurements have been limited by the presence of minor field components similar to those shown in Fig. 2.

For example, in Reference 5 it is shown that bending limits the polarisation-holding ability of birefringent fibres to a level somewhat worse than that predicted in Reference 1. However, even at very large bend radii it was found that no better than $\sim 40$ dB extinction ratio could be measured, which is the level which might be expected from the presence of minor field components. The measurement may therefore have been fundamentally limited.

*Fibre polariser characterisation:* Bow-tie fibres in which one of the polarised modes is made deliberately leaky[8] are attractive for use as polarisers. From bend loss measurements on short lengths[9] they can be extrapolated to give very high extinction ratios. However, we have more recently observed the highest measured extinction ratio to be 42 dB, a level which closely corresponds to the limit expected from the presence of the minor field component. The bow-tie fibre polariser is therefore a mode selector, being capable of selectively discriminating between the two nonplane-polarised modes in a birefringent fibre. As a linear polariser, however, it is limited to $\sim 40$ dB extinction ratio. This is not a particular disadvantage in practice, since many fibre applications in fact require a mode selector; this has been inaccurately associated with the use of a linear polariser.

*Fibre gyroscope:* Consider the arrangement shown in Fig. 3$a$ where a bulk-optic polariser is used to analyse the output

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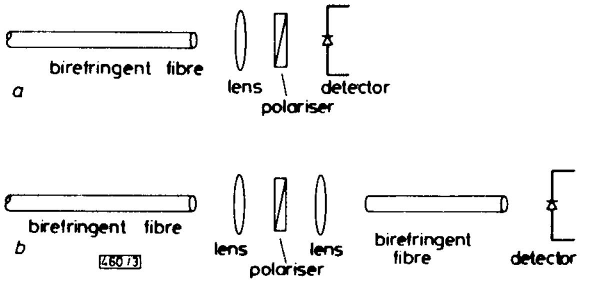


**Fig. 3** *Performance of bulk polarisers as y-polarised mode selector*

Conventional configuration (*a*) gives ~40 dB selectivity, while (*b*) gives from 80–110 dB selectivity

from a high-birefringence polarisation-maintaining fibre, such as might be used in a gyro coil. To ensure reciprocity,[4] the requirement is to select only one of the fibre modes at up to 120 dB selectively for transmission to the detector. It is clear from the foregoing that even a perfect linear-polariser is unable to achieve a mode selectivity better than 40 dB, since the modes are not plane-polarised. On the other hand, a perfect fibre polariser does achieve the required selectivity, since it discriminates against modes, not polarisation.

By placing another high-birefringence fibre B after the polariser, as shown in Fig. 3*b*, the mode selectivity increases to 80 dB (i.e. 40 dB + 40 dB), since the minor field components which pass through the polariser excite the fundamental mode of the following fibre only though its minor field components, which are −40 dB down. The following fibre therefore acts as an efficient spatial mode filter. An even more efficient mode filter would be a conventional monomode fibre where the minor field components are −70 dB down, giving a total mode selectivity of 110 dB (i.e. 40 dB + 70 dB), which approaches the figure required for the fibre gyro.[4]

*Conclusions:* The orthogonally polarised minor field component in highly birefringent fibres has been measured to be present at −40 dB below the major component. The reasons why this is ~30 dB higher than calculated for conventional fibres is not at present understood. However, the presence of such a relatively large minor field indicates that the fundamental mode can no longer be considered plane-polarised for the purposes of fibre polarisation measurements. Moreover, the commonly used linear bulk-polariser may provide insufficient mode selectivity to ensure reciprocity in the fibre gyroscope.

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## References

1 PAYNE, D. N., BARLOW, A. J., and RAMSKOV HANSEN, J. J.: 'Development of low and high birefringence optical fibres', *IEEE J. Quantum Electron.*, 1982, **4**, pp. 477–488

2 SNYDER, A. W.: 'Asymptotic expressions for eigenfunctions and eigenvalues of a dielectric or optical waveguide', *IEEE Trans.*, 1969, **MTT-17**, pp. 1130–1138

3 GLOGE, D.: 'Weakly guiding fibres', *Appl. Opt.*, 1971, **10**, pp. 2252–2258

4 KITNER, E. C.: 'Polarisation control in optical-fibre gyroscope', *Opt. Lett.*, 1981, **6**, pp. 154–156

5 RASHLEIGH, S. C., and MARRONE, M. J.: 'Polarisation-holding in coiled high-birefringence fibres', *Electron. Lett.*, 1983, **19**, pp. 850–851

6 BIRCH, R. D., PAYNE, D. N., and VARNHAM, M. P.: 'Fabrication of polarisation-maintaining fibres using gas-phase etching', *ibid.*, 1982, **18**, pp. 1036–1038

7 KATSUYAMA, T., MATSUMURA, H., and SUGANUMA, T.: 'Low-loss single-polarisation fibres', *ibid.*, 1981, **17**, pp. 473–474

8 VARNHAM, M. P., PAYNE, D. N., BIRCH, R. D., and TARBOX, E. J.: 'Single-polarisation operation of highly birefringent bow-tie optical fibres', *ibid.*, 1983, **19**, pp. 246–247

9 VARNHAM, M. P., PAYNE, D. N., BIRCH, R. D., and TARBOX, E. J.: 'Bend behaviour of polarising optical fibres', *ibid.*, 1983, **19**, pp. 679–680