4.4 CURRENT SENSORS USING HIGHLY-BIREFRINGENT BOW-TIE FIBRES

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Introduction

Faraday-effect optical-fibre current sensors have a number of well-known advantages for use in high-voltage transmission systems[1] and other hostile environments. However, these applications have been restricted by the presence of linear birefringence in the fibre which adversely interacts with the Faraday polarisation rotation produced by magnetic fields.

Linear birefringence results from (a) intrinsic effects within the fibre (ellipticity, inbuilt thermal-stress) and (b) packaging and coiling which introduces transverse pressure and bends. The first of these can be eliminated by spinning a moderately-birefringent conventional fibre during the draw to produce a fibre with negligible intrinsic linear birefringence[2]. However, the fibre remains just as sensitive to externally-induced birefringence caused by coiling. A complete solution to this problem is to design fibres with a large circular birefringence which overwhelms the perturbations caused by linear birefringence and thus permits the full Faraday rotation to be observed. Helical fibres[3] have this property, but are large in diameter which restricts their application to coils of about 15cm radius. Moreover, care is required in launching and splicing.

We report here an alternative approach which appears particularly suited to applications requiring multi-turn, small-diameter coils. A highly-birefringent Bow-Tie fibre is rapidly spun during the draw to produce a fibre which exhibits a large elliptical birefringence. Unlike the unspun Bow-Tie fibre, the fibre now exhibits a magnetic field sensitivity. In addition, just as in a normal birefringent-fibre, the fibre is resistant to polarisation mode-coupling effects and therefore the current sensitivity is largely unaffected by packaging.

Theory

Twisted linearly-birefringent fibres have been analysed here using a previously-developed coupled-mode theory[4]. The modal birefringence B for the elliptically-polarised eigenmodes of the fibre can be expressed as:

$$B = \frac{\lambda}{2\pi} \left[\sqrt{4\tau^2 + \Delta\beta^2} - 2\tau\right] \qquad (1)$$

where λ is the wavelength, τ is the twist rate and $\Delta\beta$ the local linear birefringence in the fibre. Thus the relationship between the beat length L_p' of the elliptically-birefringent spun fibre and the beat length L_p of the unspun fibre is:

$$L_p' = L_p L_t / [(4L_p^2 + L_t^2)^{\frac{1}{2}} - 2L_p] \quad (2)$$

where L_t is the twist pitch.

The beat length L_p' between the fibre elliptically-polarised modes is shown in Fig. 1 as a functin of the twist pitch L_t, for various values of unspun beat-length L_p. As an aid to fibre design, curves for values of the ratio $2L_p/L_t$ from 1 to 4 are also shown. Note that the ellipticity ϵ (minor/major axis) of the eigenmodes is given by

$$\epsilon = \tan(0.5 \tan^{-1} \frac{2L_p}{L_t}) \quad (3)$$

It should be clear that when the ellipticity approaches unity (large spin) the modes are predominantly circularly-polarised and little quenching of the Faraday effect is expected to occur. This can be seen more clearly in Fig. 2 where the computed[2] sensitivity of the fibre in a current monitor is shown for various values of $2L_p/L_t$. Although other methods are possible, we have assumed here that the arrangement used to detect the Faraday rotation is that described in ref. 1. It can be seen that the sensitivity in the linear region (Faraday rotation angle $<20°$) differs little from the perfect isotropic fibre ($2L_p/L_t = \infty$) for values of $2L_p/L_t$ greater than about 2, which means $L_t = L_p$. From eqn. (2) this value corresponds to a resultant elliptical beat-length $L_p' = 4.24L_p$. Thus to ensure a sufficiently large elliptical birefringence ($L_p' < 10$mm) we need to choose a fibre whose unspun beat-length L_p is less than 2-3mm.

Experiment

Three different elliptically-birefringent fibres have been fabricated by spinning Bow-Tie fibres. The initial linearly-birefringent beat-lengths of the Bow-Tie fibres ranged from 1.8mm to 3mm (at 633nm). Different spin pitches were chosen (7.7, 6.25 and 2.8mm) and the values $2L_p/L_t$ were (a) 2.44, (b) 1.09 and (c) 0.456.

Fibre coils with diameters of 3.3cm and 5.5cm were wound using these fibres. The number of turns on the coils were (a) 100, (b) 140 and (c) 60. The coil leads were about 1 metre long, and used the same fibre. Currents up to 400A were measured by detecting the rotation angle of the output (633nm) state of polarisation.

The experimental results are shown in Figure 3. Here the relative amplitude at the output of the polarisation detector is plotted as a function of the Faraday rotation angle $2\theta = 5.30 \times 10^{-4}\, nI$ for an isotropic fibre, where I is the current, n is the number of turns in the coil. The solid lines are calculated results for the above three cases. The experimental points agree with the theoretical prediction, although exhibiting some scatter which could be attributed largely to fluctuation in the unstabilised HeNe light source.

Since the linear birefringence of Bow-Tie fibres is temperature-sensitive, some form of temperature compensation will be needed in a practical device. This can be achieved by winding two spliced fibres which have the same length and characteristics, but opposite twist directions. The orientations of the principle axes of the two fibres are arranged to be orthogonal at the joint.

A temperature-compensated fibre coil was wound in this fashion and the results are shown in Figure 3 curve (b). As expected it has the same behaviour as the fibre having only one direction of twist. However, the temperature sensitivity was considerably reduced to the extent that normal laboratory temperature fluctuations were no longer a problem.

Conclusion

We have demonstrated that elliptically-birefringent fibres made by spinning Bow-Tie fibres can be used for detecting the Faraday effect. The detection sensitivity is more than 80% of that for the ideal case, while the resistance to external perturbations and bending remains high owing to the residual birefringence. In fact, current sensitivity is maintained in coils down to as small as 33mm in diameter. It is clear therefore that the new fibre has considerable potential for use in sensitive current monitors employing small-diameter multi-turn coils, as well as in more conventional current-measuring applications.

Acknowledgements

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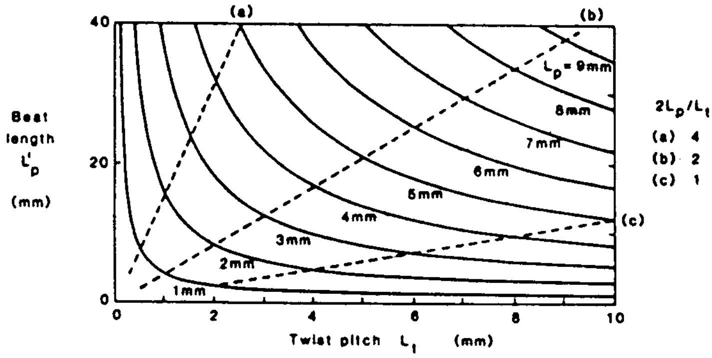

Fig. 1 Resultant elliptically-polarised beat-length L_p' calculated as a function of spin pitch L_t for various values of unspun fibe beat-length L_p. Also shown is beat-length ratio $2L_p/L_t$.

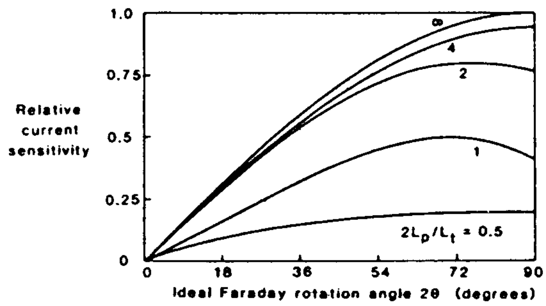

Fig. 2 Current sensitivity of a spun highly-birefringent fibre for various beat-length ratios $2L_p/L_t$. The Faraday rotation angle 2θ is that expected in an isotropic silica medium. These curves are plotted for very large total twist number (>1000).

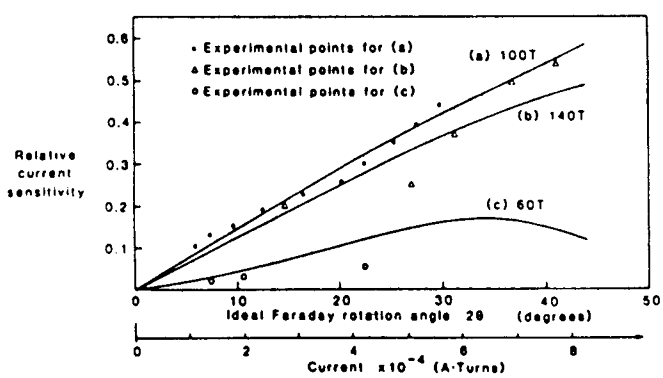

Fig. 3 Experimental results for 3 spun Bow-Tie fibres (see text).

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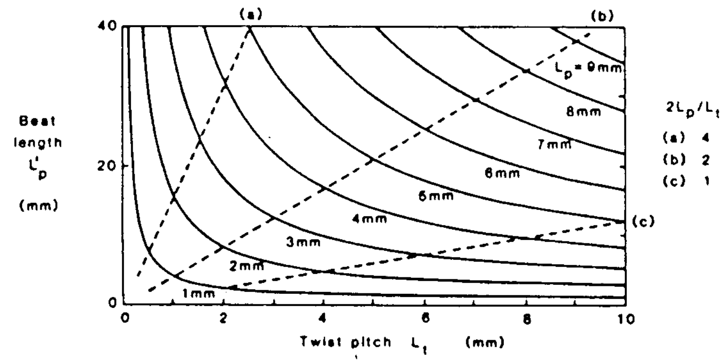

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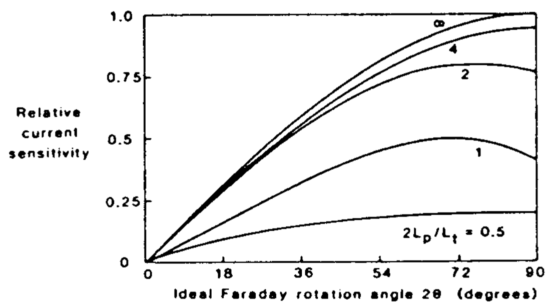

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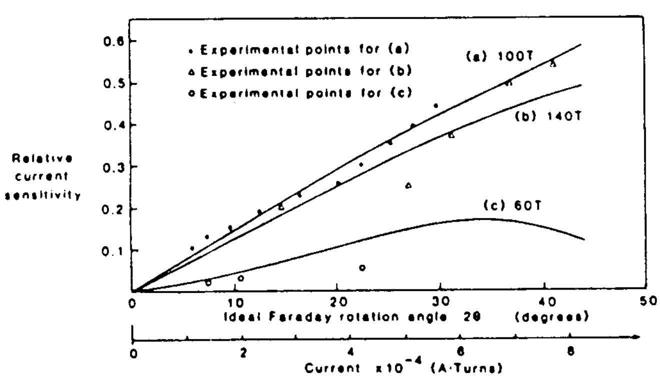

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