Miniature multi-turn fibre current sensors

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Abstract: Highly birefringent Bow-Tie fibres can be sensitized to Faraday rotation by spinning the fibres during draw. The fibres become elliptically-birefringent and this permits multi-turn small-diameter coil to be wound without loss of current sensitivity.

Introduction

The Faraday effect in optical fibres has been utilized to develop several useful fibre devices such as current sensors,[1–4] magnetometers[5] and optical isolators.[6,7] Fibre current sensors are particularly attractive for use in the electricity generating industry and other hostile environments[2,3] because they are lightweight, flexible, electrically insulating, immune from electromagnetic noise and have a rapid response.

The Faraday effect produces a rotation of the plane of polarization in proportion to the component of a magnetic field along the direction of propagation of the light. However, the Faraday rotation in a fibre device is usually small and is easily quenched by the presence of birefringence[4,8] induced by core ellipticity, asymmetric stress,[9] coiling or packaging. Thus, special fibres[9] designed to overcome these problems are of particular interest.

A very low-birefringence fibre has been demonstrated by spinning a conventional single-mode fibre during the draw.[9,10] However, although the resultant fibre exhibits extremely-low internal birefringence, it is very sensitive to external perturbations such as vibration, coiling and applied stress. The problem can be eliminated in helical-core fibres[11] which exhibit sufficiently-high circular-birefringence to overwhelm the linear birefringence caused by external perturbations. However, the diameter of the fibre has to be relatively large so as to contain the helical core and this restricts its application to coils of radius greater than about 10 cm. Moreover, care has to be taken in launching and splicing.

This paper reports electric current sensing using a new type of spun fibre which exhibits a high elliptical-birefringence. The fibres are obtained by spinning conventional highly-birefringent fibre preforms (e.g. Bow-Tie preforms) during the draw. By choosing appropriate fibre parameters and fibre-drawing conditions, a predominantly-circular birefringence can be frozen in. Large quasi-circular birefringence ensures good magnetic-field sensitivity while maintaining a high resistance to external perturbations. The new fibre allows small-diameter multi-

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turn coils to be wound without paying special attention to induced birefringence. Coils having hundreds of turns with a diameter as small as one centimetre are easily constructed, thus making fibre current sensors for very low electric currents a practical reality.

Theoretical analysis

A permanent frozen-in rotation of the birefringent axes can be obtained by spinning during drawing a fibre having high linear-birefringence. The axis rotation results in a fibre with a strong elliptical-birefringence. The magnitude of the elliptical birefringence depends on the initial linear birefringence $\Delta\beta$ of the unspun fibre and the rate of spin τ. Using coupled-mode analysis and the matrix transformation[12,13], the modal birefringence B for the elliptically-polarized eigenmodes of the fibre can be expressed as:

$$B = \frac{\lambda}{2\pi}\{(4\tau^2 + \Delta\beta^2)^{1/2} - 2\tau\}, \quad (1)$$

where λ is the optical wavelength. Applying the conventional definitions for the beat-length of the linear birefringence $L_\rho = 2\pi/\Delta\beta$ and the spin pitch $L_S = 2\pi/\tau$, corresponding beat-length of the elliptical birefringence of the fibre is

$$L_e = L_p/\{(4\varphi^2 + 1)^{1/2} - 2\varphi\}, \quad (2)$$

where φ is the ratio of the spin rate to the initial linear-birefringence of the unspun fibre.

$$\varphi = \tau/\Delta\beta = L_p/L_S \quad (3)$$

The spin ratio φ can vary between zero and infinity corresponding to a perfectly linear and perfectly circular birefringence respectively.

The beat length L_E in equation (2) is a measure of the resistance of the fibre to external perturbations and should normally be less than 10 mm to avoid significant cross-coupling between the two elliptical eigen-modes. The elliptical-mode beat-length is shown in Fig. 1 as a function of the spin pitch L_S for various values of unspun beat-length L_p. It can be seen that the resultant fibre beat-length increases rapidly as the spin pitch L_S approaches the unspun beat-length L_p. This is to be expected as it is known that large spin rates produce a low-birefringence fibre.[10] However, provided the spin pitch is not significantly less than the unspun beat-length, an acceptable increase in fibre beat-length of about four times results from the spinning process and the fibre remains substantially highly-birefringent. There is, however, a compromise to be made between the magnitude of the residual elliptical-birefringence and the current sensitivity, which can be understood as follows.

An unspun highly-birefringent fibre has very low magnetic-field sensitivity,[4] but good polarization preservation owing to its short beat-length. A highly-spun fibre,[10] on the other hand, has full Faraday sensitivity, but almost zero residual birefringence and consequent lack of resistance to external perturbations. Between these two extremes of spin rate lies a region of elliptical birefringence where sufficient residual elliptical birefringence is present to ensure good resistance to packaging effects while preserving good magnetic-field sensitivity. For the latter to be true, the modes should be quasi-circularly polarized. In fact, the Faraday

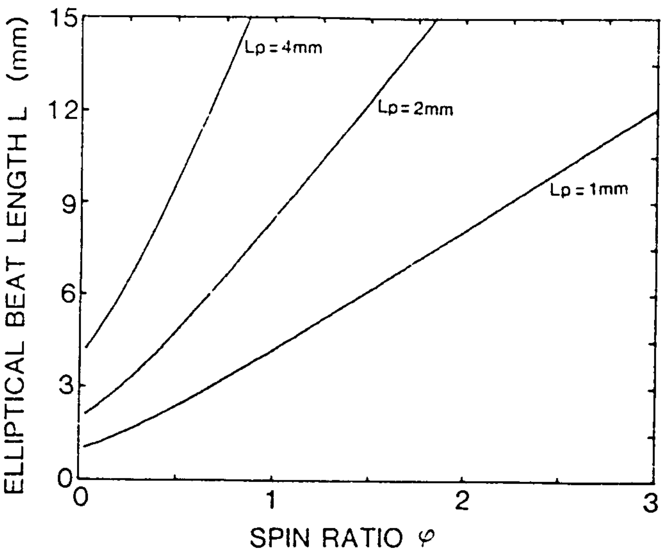

FIG. 1. Calculated elliptically-polarized beat-length L_e versus spin ratio φ for various values of unspun fibre beat length L_p. Beat-length L_e should be short for good packaging resistance.

sensitivity is directly related to the ellipticity ϵ (minor/major axis) of the polarization eigen-modes.

$$\epsilon = \tan\{0.5\tan^{-1}(2\varphi)\} \quad (4)$$

Provided the ellipticity is larger than about 0.5, circular birefringence dominates, the modes are nearly circularly-polarized and very little quenching of the Faraday rotation by the residual linear-birefringence occurs.

The Faraday rotation in the fibre is normally measured by launching linearly-polarized light along one of the principal axes of the fibre.[4] The output state of the polarization can then be analysed by detecting the intensities (I_1 and I_2) in two orthogonal directions orientated at 45° to the output principal axes. The Faraday rotation angle is related to the detected optical signal $(I_1 - I_2)/(I_1 + I_2)$, which is equal to sin $(2fz)$ for a perfectly-isotropic fibre,[1,8] where z is the length of the fibre and f is the Faraday rotation angle per unit interaction length. For a linearly-birefringent fibre, z is the maximum usable interaction length and is equal to a quarter of the polarization beat length,[4,9,10] or the length remaining after subtraction of an integral number of half beat-periods. If the fibre length corresponds to a multiple of half beat lengths, the sensitivity is zero.

For a spun birefringent fibre, however, the sensitivity increases with the spin rate.[10] Unlike linearly-birefringent fibres, the interaction length is no longer limited to a quarter of the beat length. Fig. 2 illustrates the Faraday rotation sensitivity of a spun birefringent fibre relative to that of an isotropic fibre (sensitivity=1). The curve is shown as a function of spin ratio φ for a fibre coil of 100 turns and a diameter of 3 cm with an applied current of 50 A. The relative sensitivity is above 80% when φ is greater than 1.

Using the orthogonal detection scheme, the ratio $(I_1 - I_2)/(I_1 + I_2)$ is not a linear function of Faraday rotation. The linearity of the detected optical signal corresponding to a Faraday rotation angle $2fz = 5.3 \times 10^{-4}NI$, between 0 and 30 degrees is shown in Fig. 3, where I is the applied current and N is the number of turns in the coil. It can be seen that a good linearity (less than 5% deviation) can be obtained for a Faraday rotation angle less than about 15°, depending on the total fibre length and the spin ratio. This is a fairly high Faraday rotation and indicates

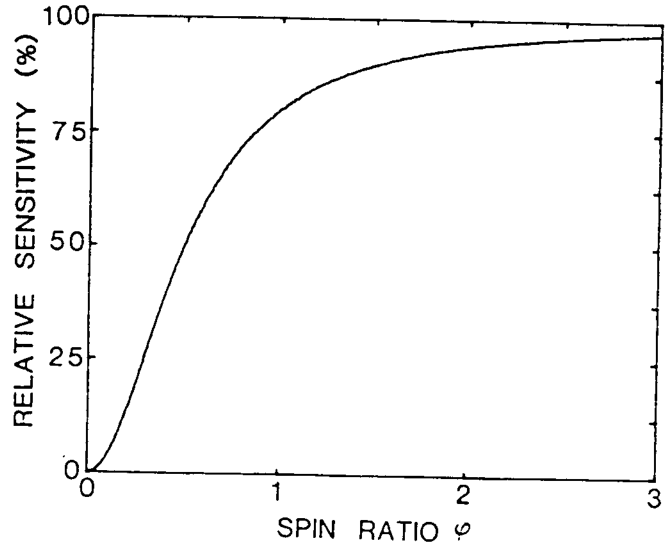

FIG. 2. Current sensitivity of a spun highly-birefringent fibre (L_p = 3 mm relative to that of an isotropic fibre versus spin ratio φ). Fibre coils have 100 turns with a diameter of 3 cm.

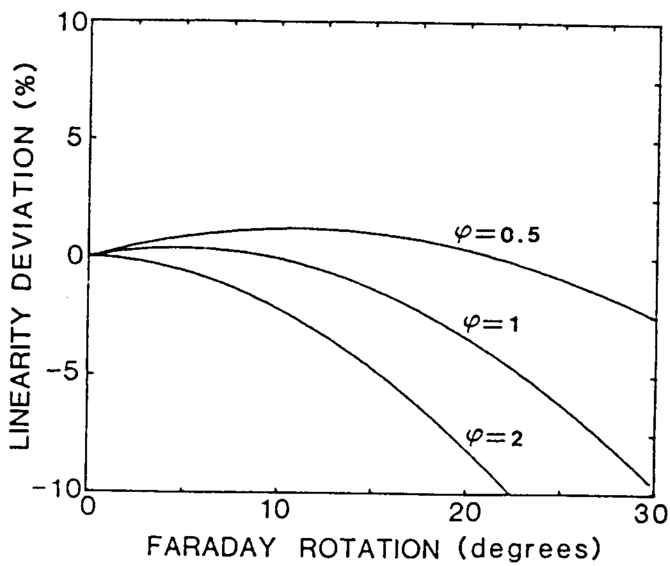

FIG. 3. Calculated linearity of the optical output versus applied current for various spin ratios φ. Results are for 100 turn coils of 3 cm diameter using a fibre having L_p = 3 mm.

that linearity can be as good as for the more conventional fibre current sensor.

In summary, the ideal fibre for use in a current sensor should have a spin ratio φ greater than 1 to ensure good sensitivity (Fig. 2), around 1 to give good linearity (Fig. 3) and less than 1 to provide high birefringence and resistance to packaging (Eqn. 2). The latter point also requires as short an unspun beat-length as possible. We have chosen a compromise spin ratio of around unity and an unspun beat-length of around 2 mm at 633 nm.

Experiment

Several different elliptically-birefringent fibres have been designed and fabricated by spinning Bow-Tie preforms[14] during fibre drawing. The initial linearly-birefringent beat lengths of the fibres ranged from 1.5 mm to 3.3 mm (at 633 nm) and the spin pitches from 2.8 mm to 7 mm. The fibres were wound into coils on 3 formers with diameters of about 3 cm, through which a current-carrying conductor was passed. The characteristics of the coils are shown in Table 1 and each had leads of about 1 m in length. Currents up to 400 A r.m.s. were measured by detecting the rotation angle (at 633 nm) of the output state of polarization. In order to do this, polarized light was injected into the fibre and the output intensity observed through an analyser. The sensitivity of the measurement was estimated to be about 10 mA.

	Coil A	Coil B	Coil C
No. of turns N	100	100	100
Diameter of coil (cm)	3	3	3
Initial fibre beat length L_p (mm)	1.5	1.5	3.3
Spin pitch L_s (mm)	7	3.3	2.8
Spin ratio φ	0.21	0.45	1.2

TABLE 1.

Fig. 4 shows the experimental results for 50 Hz high-current measurements using the three coils. In the figure the normalized optical signal at the output of the polarisation detector is plotted as a function of the applied current. The solid lines are calculated results for the above three cases. The experimental points agree broadly with the theoretical predictions, although there is some scatter which can be attributed largely to the uncompensated thermal drift of the output polarization state.

Temperature compensation

Thermal drift results from the temperature dependence of the elliptical birefring-

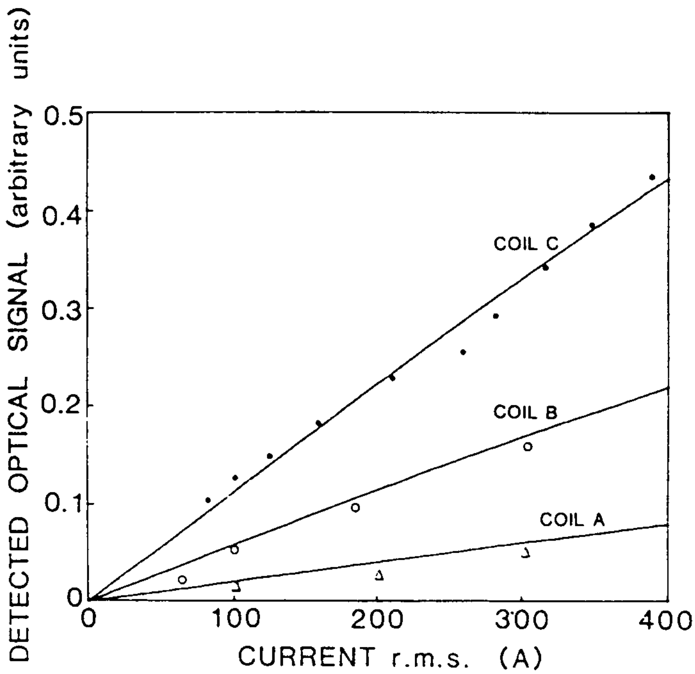

FIG. 4. Experimental results for the three coils shown in Table 1. The detected outputs are compared with theoretical predictions (solid lines).

ence in the fibre. As pointed out earlier, the elliptical birefringence is a direct result of the rotating birefringent axes in a highly linearly-birefringent fibre and its magnitude depends upon the unspun birefringence. In a Bow-Tie fibre the unspun birefringence is generated by thermal stress as a result of the differential thermal expansion[14] and is therefore strongly temperature dependent. Although the temperature dependence of an elliptically-birefringent fibre reduces with increase of spin ratio, the fibre birefringence is still temperature sensitive and the output polarization state wanders with temperature. Some form of temperature compensation will therefore be needed in a practical device. In a preliminary investigation, we have used a passive compensation scheme which has the advantages of high reliability and low cost, since very few components are required. An alternative is to use a polarization tracker or compensator at the output.

The temperature sensitivity of the output polarization-state can be considered to have two components, namely the induced circular birefringence which results from spinning, and the residual linear birefringence. If the light travels along a fibre with two identical sections which are spun in opposite directions, i.e., one has a right-hand twist and the other a left-hand, it can be shown that the thermal drift due to the circular-birefringence will cancel. Moreover, the thermal effect due to the residual linear birefringence can be compensated by interchanging the two orthogonal axes of birefringence. In practice, both compensatory mechanisms can be achieved by bifilar-winding two identical fibres with opposite spin directions and splicing them together with their principal-axes orthogonal so as to interchange the fast and slow axes (Fig. 5). The compensation thus achieved is automatic and exact in the ideal case. However, in practice, residual temperature sensitivity may

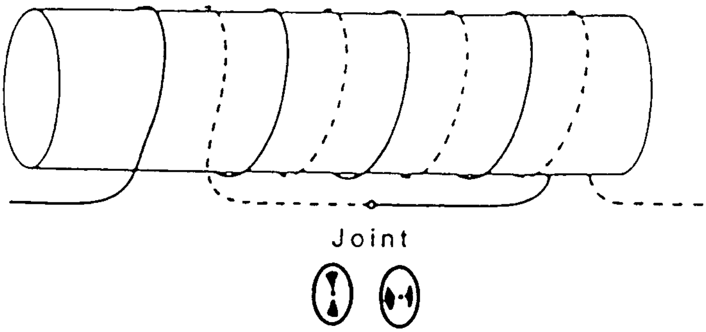

FIG. 5. Fibre current-sensor coil with temperature compensation. Two fibres spun in the opposite sense are bifilar and spliced together with principal axes interchanged.

still exist which can be attributed to differences in length of the two fibre sections, non-ideal joints and slight changes of spin-pitch.

Fibre coils of 100 turns with a diameter of 3 cm wound in the above fashion were tested at temperatures ranging from 0°C to 100° C. The best result was obtained by adjusting one fibre section length to achieve a matched condition, at which point the two sections have the same number of twists but slight differences in fibre length. However, although a considerable improvement on the uncompensated case, the thermal drift was not compensated completely and some fluctuations due to residual linear birefringence were observed.

Similar results were obtained using a reflection method employing broadly the same operating principle as the above method. Here only one section of the fibre is needed, the second fibre being replaced by a mirror butted to the fibre end. The other end of the fibre was spliced to a fibre coupler, as shown in Fig. 5. The unused end of the coupler was immersed in index matching liquid.

The advantage of the reflection method is that the total number of turns for light travelling forward and backward are always equal. However, although the induced

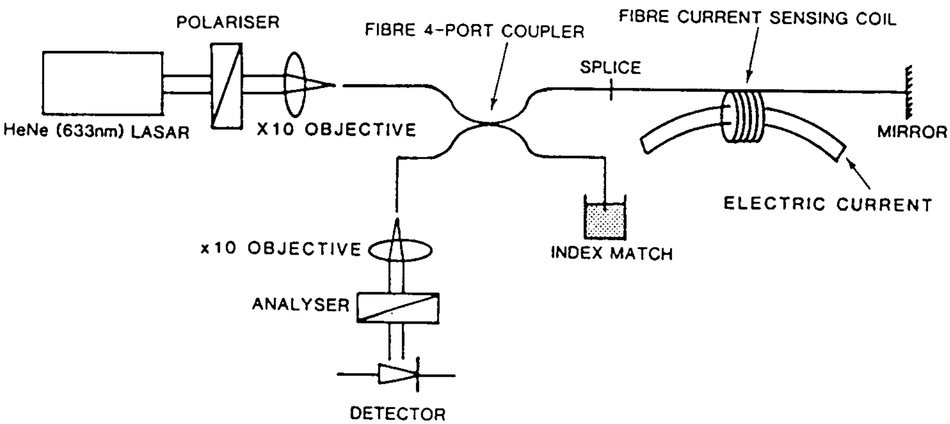

FIG. 6. Schematic diagram of the reflection stabilization experiment.

circular birefringence component of thermal drift can be compensated, the linear birefringence cannot and thus some thermal drift will be present. In fibres with a large spin ratio where the residual linear birefringence is small, the scheme may be acceptable. Preliminary experiments have shown the viability of the technique (± 20% thermal drift), but further work is required before a target drive of ± 5% can be achieved.

Conclusion

The two eigen-modes in a spun highly-birefringent fibre are elliptically-polarized. The beat-length resulting from the difference between their propagation constants can be short and this is an important parameter in governing the resistance to external effects. In addition, the fibres retain their sensitivity to Faraday rotation and are therefore ideally suited for use in current sensors.

Coils of 100 turns with diameters of 3 cm have been made and are used to measure currents from 10 mA to 400 A. Some thermal drift is present and two methods have been investigated as a means of compensation.

The new fibre has considerable potential for use in sensitive current monitors employing small-diameter multiturn coils, as well as more conventional current-measuring applications.

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References

1. Smith, A.M. Polarisation and magneto-optical properties of optical fibres. *Appl. Opt.* **17,** 400 (1978).
2. Rogers, A.J. Optical measurement of current and voltage on power systems. *IEE J. Electron. Power App.* **2,** 20 (1979).
3. Papp, A. and Harms, H. Magneto-optical current transformer. *Appl. Opt.* **19,** 3729 (1980).
4. Rashleigh, S.C. and Ulrich, R. Magneto-optic current sensing with birefringent fibres. *Appl. Phys. Lett.* **34,** 768 (1979).
5. Bergh, R.A., Lefevre, M.C. and Shaw, H.J. Geometrical fibre configuration for isolators and magnetometers. *Proc. 1st Int. Conf. Fibre-Optic Rotation Sensors,* 400 (1981).
6. Findakly, T. Single-mode fibre isolator in toroidal configuration. *Appl. Opt.* **20**, 3989 (1981).
7. Warbrick, K. Single-mode optical isolator at 1.3 um using all-fibre components. *Electron Lett.* **22**, 711 (1986).
8. Ulrich, R. and Simon, A. Polarisation optics of twisted single-mode fibres. *Appl. Opt.* **18,** 2241 (1979).
9. Payne, D.N., Barlow, A.J. and Ramskov Hansen, J.J. Development of low and high birefringence optical fibres. *IEEE J. Quan. Electron.*, p. 477 (1982).

10. Barlow, A.J., Ramskov Hansen, J.J. and Payne, D.N. Birefringence and polarisation mode-dispersion in spun single-mode fibres. *Appl. Opt.* **209**, 2962 (1981).
11. Varnham, M.P., Birch, R.D. and Payne, D.N. Helical-core circularly-birefringent fibres. *Proc. IOOC-ECOC, Venice, 1985.*
12. McIntyre, P. and Snyder, A.W. Light propagation in twisted anisotropic media — application to photo-receptors. *J. Opt. Soc. Am* **68**, 149 (1977).
13. Huang, H.C. and Qian, J.R. Theory of imperfect nonconventional single-mode optical fibres, in *Optical Waveguide Sciences.* Martinus Nijhoff, The Hague, p.57 (1983).
14. Birch, R.D.,Payne, D.N. and Varnham, M.P. Fabrication of polarisation-maintaining fibres using gas-phase etching. *Electron Lett.* **18**, 1038 (1982).