Current Monitor Using Elliptical Birefringent Fibre and Active Temperature Compensation

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Abstract

Highly-elliptically birefringent fibres have been obtained by spinning a linearly-birefringent fibre during the draw. These fibres are particularly interesting for use in Faraday-effect fibre current monitors, since, in contrast with conventional fibres, they can be wound in small multi-turn coils and retain their sensitivity. We show that here the fibre output state of polarisation can be controlled to compensate for environmental perturbations using only one remote active element. Using a compact 80-turn fibre coil, currents up to 370 A rms have been measured, with a maximum sensitivity of 100μA rms $Hz^{-1/2}$.

Introduction

A number of optical-fibre current monitors based on the Faraday effect have been described[1,2,3]. All have in common the requirement that linear birefringence in the fibre must be eliminated in order to prevent it interfering with the small Faraday polarisation-rotation induced by the electric current. Low birefringence fibres[4] or twisted fibres[5] are generally used. The requirement for negligible residual linear-birefringence places a severe restriction on the size of the fibre coil and the number of turns which can be used, since bending and packaging readily reintroduce linear birefringence. Ideally a fibre which is resistant to packaging effects should be employed, such as a strongly circularly-birefringent fibre[6]. However, these fibres are difficult to bend owing to their large diameter and are therefore better suited to large coils of a few turns, as typically used in power-utility current monitoring.

The problem has recently been overcome[7] by the development of fibres which exhibit large elliptical-birefringence. The fibres are made by spinning highly linearly-birefringent Bow-Tie fibres during the drawing process so as to impart a built-in rotation of the birefringent axes. By careful choice of the spin rate relative to the linear birefringence, the resulting elliptically-polarised eigenmodes can be made quasi-circular and the fibre response to magnetic fields then approximates that of an isotropic or circularly-birefringent fibre. The advantage of the approach is that the fibres still retain a sufficiently large value of elliptical birefringence to impart a high resistance to external perturbations. Thus very small, multi-turn coils can be wound and this enables an extension of the sensitivity of fibre current monitors into the sub-milliamp region.

A disadvantage of the spun-birefringent fibre approach is that being dependent on the thermal-stress induced linear-birefringence, the resulting elliptical birefringence is therefore temperature dependent. The output polarisation state from the current monitor will drift slowly with time and must be either tracked or compensated. We report here a simple remote compensation scheme which uses only one active element to achieve polarisation control.

Theory

The net birefringence of a spun fibre can be represented by two lumped birefringent elements, a retarder $R(z)$ with principal-axis orientation $\phi(z)$, and a rotator $\Omega(z)$. The retardation and rotation along the fibre as a function of length z can be expressed in terms of the unspun linear-birefringence $\Delta\beta$, spin twist rate ζ and Faraday-induced rotation angle per unit length f by[4]

$$R(z) = 2 \sin^{-1} \left\{ \frac{1}{(1+q^2)^{1/2}} \sin \gamma z \right\} \tag{1}$$

$$\Omega(z) = \zeta z + \tan^{-1} \left\{ \frac{-q}{(1+q^2)^{1/2}} \tan \gamma z \right\} \tag{2}$$

$$\text{where } q = \frac{2(\zeta+f)}{\Delta\beta} \tag{3}$$

As a result of its departure from pure circular birefringence, the current sensitivity of the elliptically-birefringent fibre employed was 0.85 of that of an ideal fibre[7]. In addition, it should be noted that, in contrast to a circularly-birefringent fibre, the sensitivity depends on the input and output polarisation alignment. Nonetheless, the control loop will stabilise the fibre output even in the presence of alignment errors.

Results

Ten turns of wire were fed through the coil to provide an equivalent current of 1A rms. The current was then measured optically using the ratio technique, as previously described. The result was displayed on a signal analyser in order to identify the noise sources. Figure 2 shows a typical current measurement in which the current was a 10kHz sine wave. Here the measurement range was 0 to 25.6kHz and the resolution bandwidth 48Hz. The measurement is referenced to the sensitivity calculated for the coil using the known spin/birefringence ratio[7] and assuming a Verdet constant of 4.54×10^{-6} radians/ampere^{2}. The optical and direct measurements of current are in excellent agreement and demonstrate the high sensitivity of the current monitor. Although only 0.2mW of optical power was received, the fibre transducer sensitivity at 10kHz is 100 μA rms.Hz$^{-½}$ for 1 turn of the conductor, which is equal to the calculated shot-noise limit. However, the device suffers from a noise component at ~ 15kHz, which is attributable to the switching power supply of the HeNe laser, and low-frequency noise.

Figure 3 shows the low-frequency noise in more detail. Here the measurement range was 0 to 1.6kHz with a resolution bandwidth of 3Hz. It can be seen that the current sensitivity is limited by 1/f-type noise to about 100mA in the range DC to 300Hz, but at frequencies above this tends to the shot-noise limit. Further investigations show that the low-frequency noise is attributable to wavelength instabilities in the laser source (frequency jitter) which interact with the fibre birefringence ($\Delta\beta$ is wavelength dependent) and result in polarisation instabilities at the output of the fibre. The effect was found to vary slightly with make of laser used. The use of a stabilised single-mode HeNe laser should reduce this limitation considerably.

Currents up to 370A rms. (the limit of our generating capability) were also measured using the coil and a single wire turn. Figure 4 demonstrates the linearity of the device, the comparison accuracy being limited largely by the accuracy of the copper current-transformer measurement.

The bandwidth of the present device is limited by the processing electronics to 150kHz. The fundamental bandwidth limit is caused by transit-time effects in the coil which in our case gives a bandwidth of ~13MHz (7.5m fibre length). This serves to emphasise a further benefit of small fibre coils, since the transit-time can be minimised and provide high bandwidth.

Conclusions

A current monitor incorporating 80 turns of spun highly-birefringent fibre has been demonstrated. The fibre was tightly coiled to a diameter of 30mm without special precautions. No significant reduction in sensitivity occurred due to linear birefringence effects.

Active compensation for environmental drifts in the output polarisation state has been demonstrated using a piezo-electric fibre stretcher. The approach enabled accurate current measurements up to 370 A rms, with a sensitivity of 100μA rms.Hz$^{-½}$ for 1 turn of the conductor. Further work using a larger number of turns and more injected power should result in even greater sensitivity, possibly of a few microamps.

References

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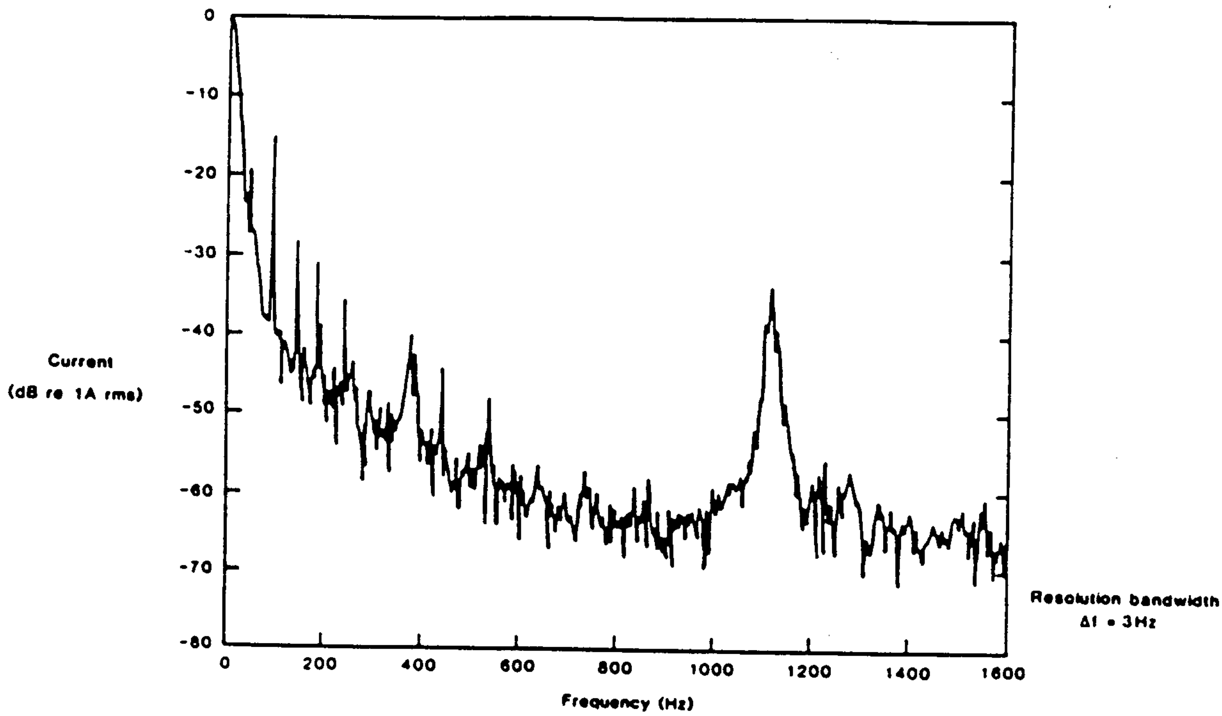

Figure 3 Spectral plot showing the noise floor of the fibre current monitor in the frequency range to 1.6 kHz

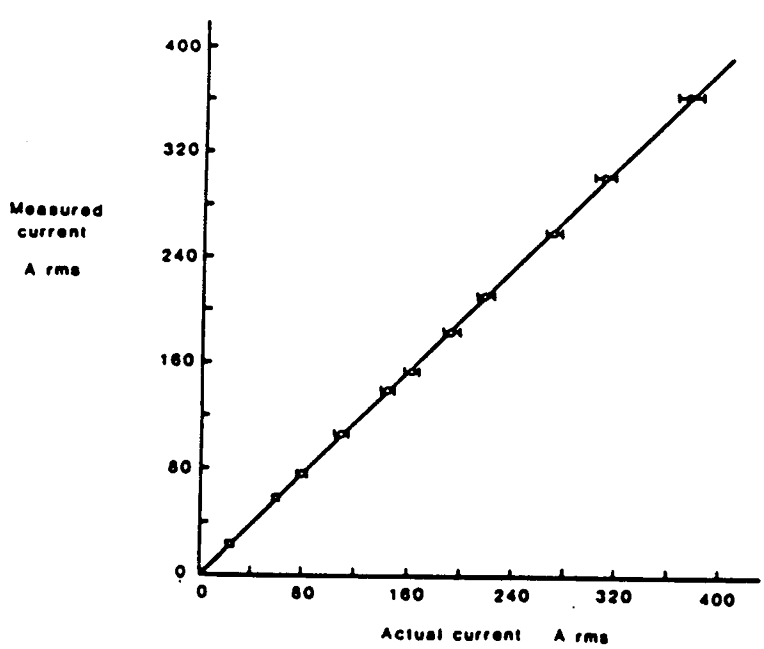

Figure 4 A graph showing the linearity of the fibre current monitor