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POLARISATION CONTROL IN RESONANT-RING FIBRE GYROSCOPES

R.J. Mears, M.P. Varnham, D.N. Payne and A.J. Barlow

Department of Electronics, The University, Southampton, UK.

The polarisation requirements of the resonant-ring fibre gyroscope are analysed. A birefringence-dependent scale factor error and zero stability problem are elucidated. Reduction of these errors using birefringence modulation and differential attenuation are discussed.

1. Introduction

The optical-fibre resonator gyroscope (Figure 1) is currently under investigation [1] as an alternative to conventional interferometric designs. Because a much shorter fibre loop is used, the resonator's sensitivity to time-dependent perturbations is greatly reduced, as is the cost. In common with other configurations, stringent control of polarisation [2] is necessary to ensure reciprocal paths for the counter-propagating light beams. High-birefringence fibres may be used to achieve this, but accurate alignment of polarisers outside the loop is still required. Ezekiel has indicated [1] that a better solution is to use a fibre with differential attenuation between the two polarised modes i.e. a polarising fibre [3].

In this paper the first analysis of the polarisation requirements of the resonator gyro is presented. The approaches of using highly-birefringent fibre with and without differential attenuation are compared, and a birefringence-induced scale factor error and rotation rate bias are evaluated. Methods are discussed for reducing these errors to acceptable limits.

2. Birefringent Fibre Resonator Without Mode-Coupling

The technique of using a fibre resonator to detect inertial rotation has been discussed elsewhere [1]. Non-reciprocal phase shifts cause the clockwise and counter-clockwise cavity resonances to be shifted in frequency by an amount Δf, given by

$$\Delta f = \frac{\Delta\Phi_{NR}}{2\pi L} \cdot v_g \qquad (1)$$

where v_g is the modal group-velocity evaluated at the resonance frequency and L is the length of the ring. The non-reciprocal phase shift $\Delta\Phi_{NR}$ comprises a Sagnac phase shift proportional to rotation rate and any other spurious phase shifts which may be present. The latter are interpreted as a rotation rate bias. A potential source of such bias is fibre birefringence which creates two orthogonally-polarised modes (x and y) resonant at different frequencies. Since in practice it will not be possible to launch a single polarised mode, the presence of the second mode in small amounts will induce phase shifts [4] in both the clockwise and counter-clockwise cavity resonances. In order to calculate the resulting non-reciprocity it is necessary to consider the relative phase shift of the two resonances. If there is no inertial rotation the two phase shifts are identical, so there is in fact no rotation rate bias. However, in the presence of inertial rotation, the two resonances occur at different frequencies and as a result, fibre polarisation mode-dispersion gives rise to a phase shift which is linearly dependent upon rotation rate. The resulting scale factor error depends on birefringence fluctuations in the ring (and hence on temperature and wavelength) and should be minimised.

Figure 2 shows the amount of round-trip differential attenuation inside the loop required to reduce this error to 10, 1, and 0.1 ppm respectively for a birefringence, $B = 10^{-3}$. The combined polarisation extinction ratios required to achieve these levels using polarisers placed outside the ring would be 20, 30 and 40dB respectively. It can be seen that for a resonator with a finesse of 100, a mere 3dB round trip differential attenuation will reduce the scale factor error to 1 ppm. A 30dB polariser would have a similar effect. Whichever method is eventually chosen, it would appear from this simple analysis that the polarisation control necessary for scale factor stability in the resonator gyroscope can be readily achieved.

3. Birefringent Fibre Resonator With Mode Coupling

Unfortunately in any real fibre resonator, finite coupling between the polarised modes will occur, either in the fibre, or in the coupler. The effect of such coupling is to give rise to a significant additional relative phase bias between the clockwise and counter-clockwise cavity resonances which will be fully analysed elsewhere. Here we consider the case of a single mode-coupling point in the resonator coupler, as shown in Fig. 3. Although a number of coupling terms arise, the dominant effect is due to coupled light from the throughput (suppressed) y-mode which interferes with the x-polarised mode at the detector. This interference term depends on the relative phase, $\Delta\theta$, of the two polarised modes at the coupling point which will not in general be identical for the two resonator inputs, since we use different input leads for the clockwise and counter-clockwise beams. The interference term gives rise to a phase error in each resonance given by

$$\Delta\Phi \simeq \frac{\pi}{\mathcal{F}} . \delta . \epsilon \cos \Delta\theta \qquad (2)$$

where δ is the magnitude of the amplitude coupling, ϵ is the amplitude extinction ratio of either polariser and $\mathcal{F}$ is the resonator finesse. Note that the resulting rotation rate bias will drift as birefringence changes in the leads cause $\Delta\theta$ to vary.

In practice the significant coupling points will be at the polarisers and throughout the resonator coupler. Various interference terms arise but the dominant effect will still be due to coupling of the throughput y-polarised mode into the orthogonal x mode as described by eqn. (2). Choosing typical values of δ and ϵ corresponding to a 60dB polariser and a 40dB polarisation-maintaining coupler [5], this phase error yields a rotation rate bias two or three orders of magnitude larger than a typical shot-noise limited rotation rate. (Calculated for 1mW on detector, quantum efficiency 0.3, 1s integration time). Thus birefringence fluctuations in the input leads will give the resonator gyroscope serious long-term drift problems which cannot be reduced by the introduction of differential attenuation in the ring. However, the dependence of the interference terms on the birefringence of the leads suggests that the bias and its associated drift can be reduced by modulating the lead birefringence.

If the lead birefringence (i.e. $\Delta\theta$) were modulated at a frequency much greater than the closed loop bandwidth of the gyroscope and with a modulation amplitude of $2\pi N$ (i.e. N beat length changes), then the apparent phase error seen after the detector will average to zero. Thus it should be possible to reduce the drift to below the shot-noise limit in a typical gyro.

4. Conclusion

A birefringence-dependent scale factor error in the resonator gyroscope can be reduced to below 1ppm either by using polarisers external to the ring, or by introducing a small differential attenuation between the two polarised modes. Polarisation mode-coupling in the resonator or in the polarisers gives rise to a potentially serious bias stability problem. Mechanical modulation of the lead birefringence prior to each input polariser can be used to reduce this drift to below a typical shot-noise-limited rotation rate.. We note that the resonator gyroscope zero stability problem arises because this gyroscope is a dual-input device and is therefore fundamentally non-reciprocal.

The design of a resonator gyro involves a trade-off between reducing the ring birefringence to reduce the scale factor error and increasing the birefringence to reduce mode coupling and its related zero stability problem. Nevertheless, indications are that 1 ppm scale factor error and shot-noise-limited zero stability may be achievable.

4. References

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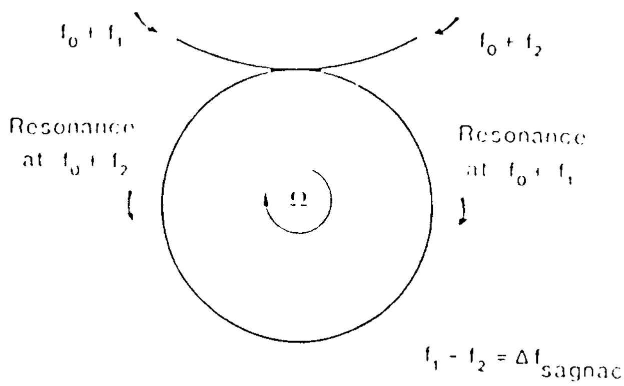
Fig. 1 Schematic of resonator gyroscope.



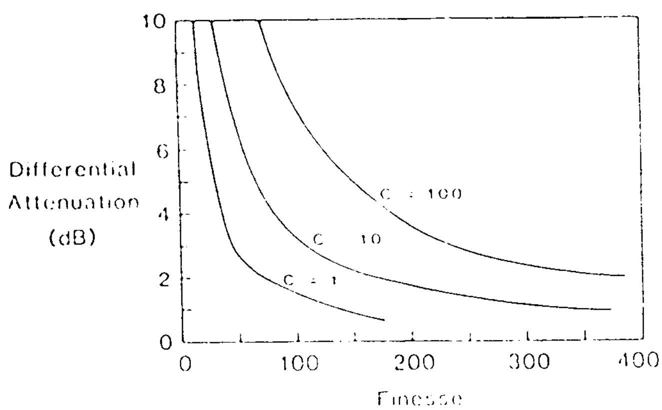


Fig. 2 Reduction of scale factor error with differential attenuation and resonator finesse

$C = 10^4 B/ppm$

B = birefringence

ppm - scale factor error in parts per million

Fig. 3 Single mode-coupling point