Frequency Modulated Heterodyne Optical Fiber Sagnac Interferometer

BRIAN CULSHAW AND IAN P. GILES

Abstract—This paper describes a new approach to the detection of rotation rate using the optical fiber Sagnac interferometer. An inherently reciprocal heterodyne system gives the advantages in terms of signal-to-noise ratios (SNR's) of heterodyne detection, while independent electronic monitoring of each propagation path through the interferometer significantly enhances signal processing flexibility. The system may thus be used as a probe to evaluate fiber properties in a way compatible with other architectures, and these measurements should lead to advances in performance characteristics. A prototype system has exhibited noise levels in the region of 100°/h, and improvement to the signal processing will soon improve on this figure.

I. Introduction

The optical fiber gyroscope offers significant potential as a sensitive navigational instrument. Currently reported sensitivity levels, measured at about 1°/h [1]-[3], are above those to be anticipated theoretically [4]. The reasons for this are becoming understood, but present knowledge is far from complete. Most systems reported to date are very similar in overall architecture, and as such have similar limiting properties in their performance. They are based on homodyne detection techniques with superimposed phase bias to optimize the interferometer sensitivity.

In this paper a novel heterodyne detection technique is described. This technique maintains the inherent reciprocity of the interferometer, but also offers a significant increase in signal processing flexibility since each propagation direction in the loop is separately accessed. This is compatible with the use of the system as a probe to measure fiber propagation properties, and these measurements should encourage further developments in the achievable sensitivity of the gyroscope. Results to date are encouraging, although the system is still in the early stages of development.

II. Heterodyne Detection

A different approach to the detection using a heterodyne detection technique is described. This method overcomes the $1/f$ noise problems and avoids amplitude modulation effects which do not influence synchronous detection. This system (Fig. 1) maintains total symmetry and identical frequencies are propagated in each direction. The use of a high local oscillator power offers great improvements in detected signal-to-noise ratios (SNR's), and a suitably polarized reference beam ensures that the system operates in a single polarization mode.

The system is based upon the well-known Mach-Zehnder heterodyne interferometer. A beam of light from the source is split by a beamsplitter B.S.1 (Fig. 1). The transmitted portion is again split by B.S.2 to be launched into a fiber loop and through a Bragg cell to be recombined by B.S.3 and detected by detector 2. The beam reflected by B.S.1 is split by B.S.3 and recombined by B.S.2 to be detected by detector 1. This interferometer is two interdependent Mach-Zehnder interferometers. Detector 2 has an IF output, set by the Bragg cell, with phase information due to the propagation in one direction through the fiber and detector 1 gives the IF with phase information due to the opposite propagation direction. The phase difference between the two IF outputs is now the required nonreciprocal phase difference between the two fiber paths. This system has the advantages of a true heterodyne system and maintains the Sagnac reciprocity. A high local oscillator power ensures shot noise limited operation of the p-i-n detectors and limiting the IF signals avoids AM noise. Each detector detects the combination of two beams which are delayed with respect to one another by approximately the propagation time through the fiber which sets a requirement on the source of a coherence length greater than the fiber length. This implies that both Rayleigh backscatter signals and discrete reflected signals will mix coherently with the signal transmitted in the opposite direction to give a phase error [5].

Initial measurements were made on this system using a single-mode HeNe laser, 80 MHz solid-state Bragg cell, pellicle beamsplitters (to preserve polarization), and 130 m of single-mode fiber wound on a 10 cm radius drum. The outputs from the detectors had large AM signals which were removed by hard limiting and the two phase modulated IF signals compared in a phase sensitive detector.

Rotation was detected with this system and noise levels of approximately 5°/s were observed which were of the same order as calculated for the end reflections of the fiber. The noise was sinusoidal of varying frequency caused by the vibration of the fiber ends.

Coherent mixing with unwanted signals was expected and it was, therefore, necessary to destroy the coherence of the unwanted signals. A long coherence length source is required in this system, so a method of coding the signal to eliminate reflection effects was adopted. The coding technique used is based on the concepts of frequency modulated radar systems and consists simply of applying a frequency ramp to the output from the laser.

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B. Culshaw is with the Ginzton Laboratory, Stanford University, Stanford, CA 94305, on leave from the Department of Electronic and Electrical Engineering, University College London, London, England.

I. P. Giles is with the Department of Electronic and Electrical Engineering, University College London, London, England.

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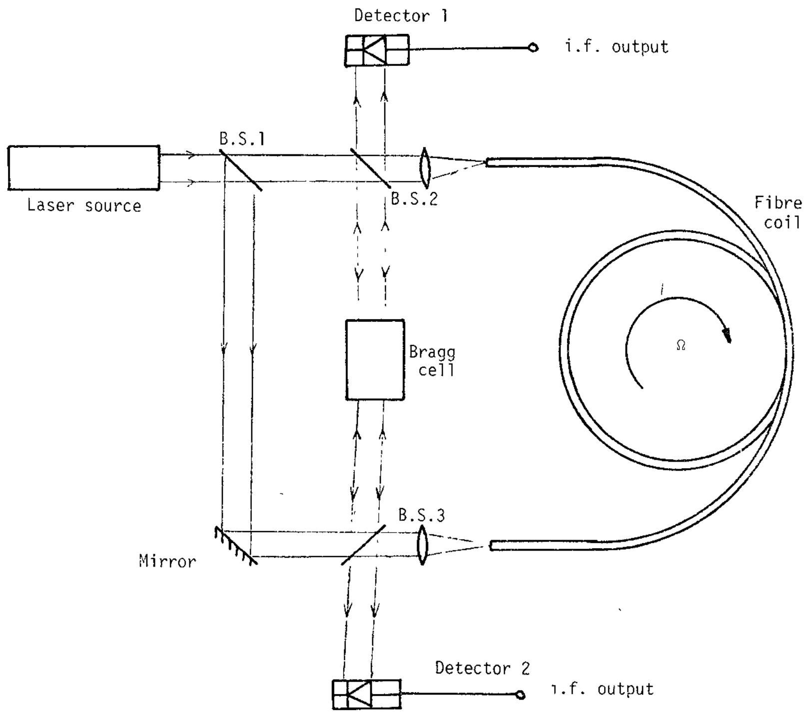

Fig. 1. Heterodyne optical fiber gyroscope.

III. FM Gyroscope

For a laser input signal which is linearly ramped in frequency the signals combined by the beamsplitters have a frequency difference dependent upon the time delay through the fiber. Any other signals such as backscatter and reflections have different time delays and appear at different frequencies. For a triangular frequency ramp (Fig. 2), the output of each detector is $fo + \Delta f$ or $fo - \Delta f$, dependent on the slope of the ramp (where fo is the IF and Δf is the frequency difference associated with delay $\Delta\tau$ for a linear ramp).

$$\Delta f = \frac{2 fm \Delta\tau}{T}. \tag{1}$$

fm is the maximum frequency deviation of the input and T is the period of the ramp waveform.

The contribution from backscatter for this ramp is dependent upon the detection bandwidth (δf). The effective length of fiber contributing to coherent backscatter is

$$\Delta l \simeq \frac{\delta f \cdot L}{\Delta f}. \tag{2}$$

For $\delta f \simeq 100$ Hz and $\Delta f = 100$ kHz $\Delta l \simeq 1$ cm per 100 m of fiber.

The detected outputs from an ideal FM system would then be the IF at fo with two sidebands at $fo \pm \Delta f$ (Fig. 3). The signal at fo is due to fiber end reflections and the noise level between fo and Δf is increased by backscatter effects. These outputs are then filtered to reduce unwanted effects and compared in a phase sensitive detector. The triangular frequency ramp must, of course, be applied periodically, and so the ideal spectrum shown in Fig. 3(a) cannot be achieved. In practice, the periodicity of the ramping function causes additional sidebands to appear spaced by $1/T$ around the ideal spectrum [Fig. 3(b)].

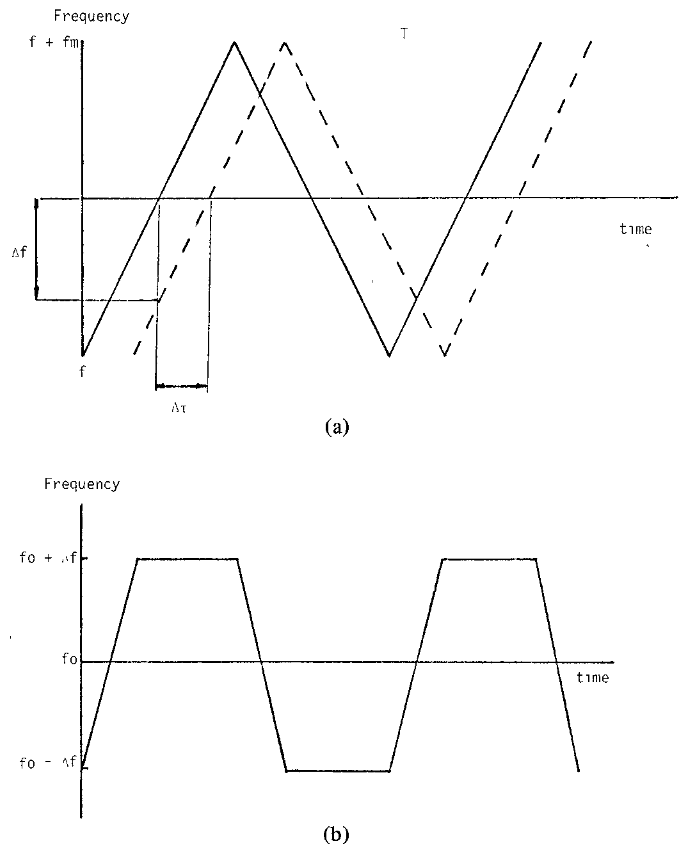

Fig. 2. Frequency modulation. (a) Frequency ramp applied to optical signal. (b) Detected output.

This system was implemented using a second Bragg cell at the laser output as the FM source. This was an 80 MHz solid-state Bragg cell which was modulated by a triangular waveform varying from 70 MHz to 90 MHz. To obtain high Δf at the

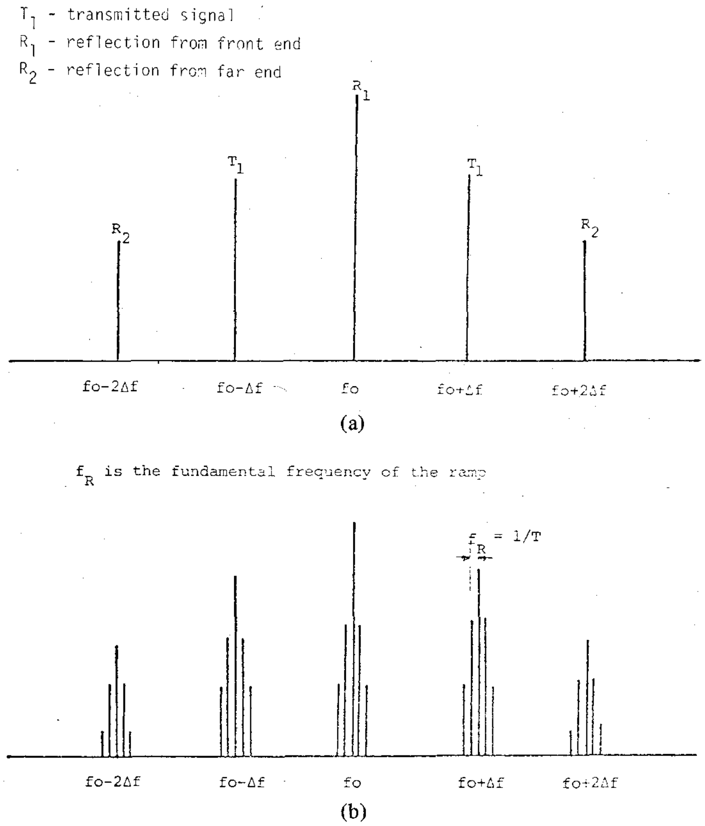

Fig. 3. FM gyroscope detector output spectrum. (a) Ideal. (b) From periodic ramp.

output for 130 m of fiber, high ramp rates were required ~5–10 kHz fundamental ramp frequency. Detected output for the system was displayed by a spectrum analyzer (Fig. 4). The SNR for the transmitted signal is 40 dB. The envelope of frequencies can clearly be seen and also the reflection noise around the IF. Secondary peaks are seen at twice the signal frequency which have been shown to be end reflections of the fiber by blocking the input to one end of the fiber. The wide envelope of the signal and the nonsymmetrical shape is caused by the spatial variation of the beam by the swept Bragg cell and the inability of the VCO and Bragg cell to respond to the high ramp rates required. Initial measurements on this gyroscope were made showing a rms noise equivalent rotation rate of ~100 deg/h. This high noise level can be assigned largely to drifts between the two high Q filters used on each detection channel, and methods of reducing this electronically induced noise are at present under investigation.

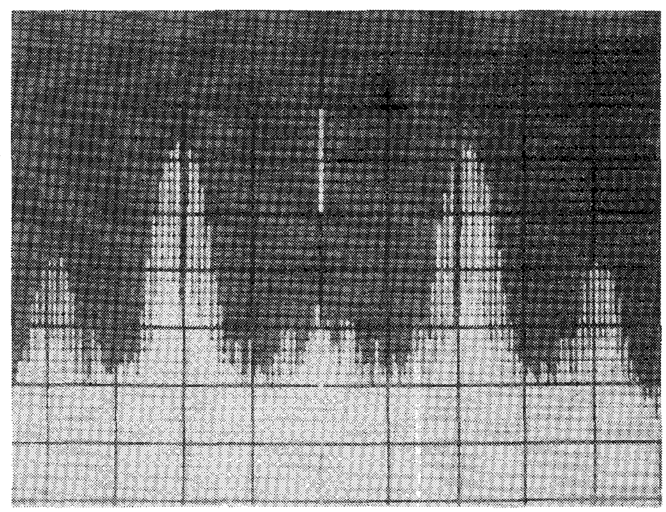

Fig. 4. Output from one detector of prototype gyroscope.

IV. Discussion

The system as described demonstrates a new approach to the detection of rotation using the Sagnac effect. There are many aspects of the system which require further investigation, but it does allow complete electronic signal processing which will be invaluable in characterizing and eliminating fiber induced noise phenomena.

The primary problem in the present system is the Bragg cells which require high power drives at high frequencies, potentially introduce nonreciprocal effects in the IF section, and produce an alignment variation in the input beams. To overcome this and improve the output spectrum, a frequency ramped single-mode laser will be used (Fig. 5). The system detects the frequency difference (Δf) through one detector and locks this to an external crystal oscillator by a feedback network to stabilize the laser ramp.

This system incorporates all the advantages of the previously discussed heterodyne gyroscope and is much simpler and far more stable. Initial characterization of this system is in progress.

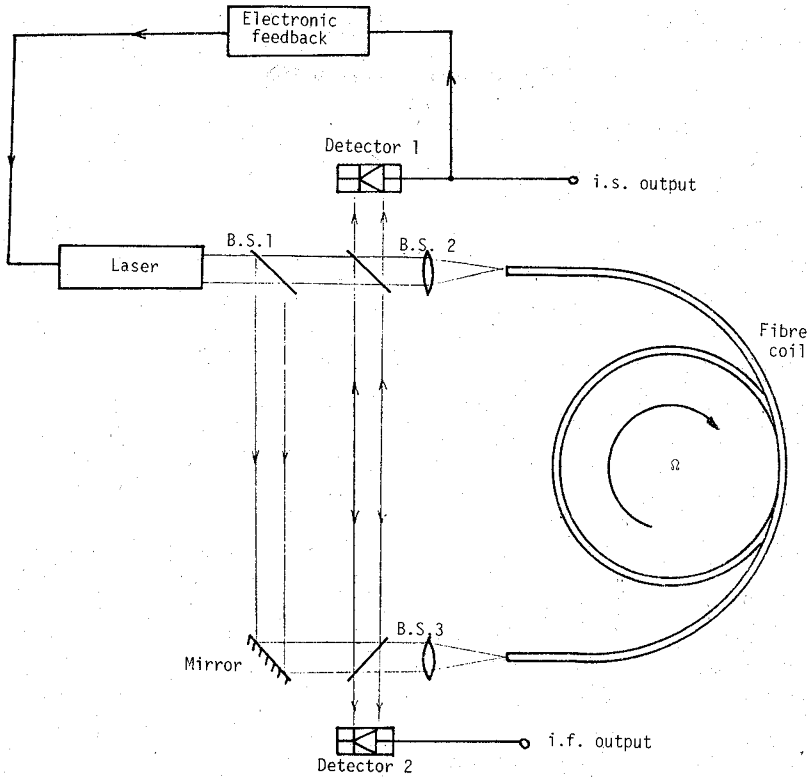

Fig. 5. FM gyroscope using a direct laser modulation method.

V. Conclusions

This paper has described a unique heterodyne detection system for use in optical fiber gyroscopes. The detection system is at present in an early stage of development, but the results obtained to date are promising with noise levels approaching those in state of the art systems. The required steps to improve on this performance are well defined and significant improvements appear possible. The accessibility of both propagating signals to electronic processing and analysis also means that the system may be used as a probe to monitor the propagation of the light in each direction in the fiber. This additional flexibility should enhance current understanding of the operation of the instrument and this should, in turn, produce higher levels of performance.

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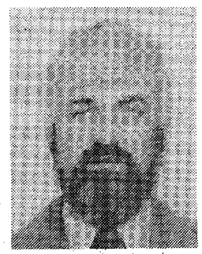
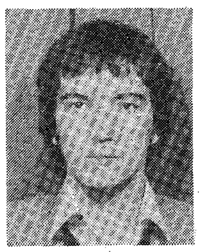


Brian Culshaw received the Honours degree in physics in 1966 and the Ph.D. degree in electrical engineering in 1969 from University College London, London, England.

In 1970 he became a Research Fellow at Cornell University, Ithaca, NY, where he continued his work on microwave semiconductor devices. From 1971 to 1973 he was a member of the Scientific Staff at Bell-Northern Research, Ottawa, Canada, and in late 1973 he returned to University College as a Research Fellow. In 1975 he was appointed a Lecturer in the Department of Electronic and Electrical Engineering, where his research work centers upon optical systems for communications, signal processing, and measurement. Presently, he is on leave at the Ginzton Laboratory, Stanford University, Stanford, CA.



Ian P. Giles received the Honours degree in physics in 1975 from the University of Surrey, Surrey, England, and the M.Sc. degree in microwaves and modern optics in 1978 from University College London, London, England.

From 1975 to 1978 he was a Microwave Engineer at the Research Laboratory of Marconi Avionics, Ltd. Currently, he is working on the Ph.D. degree at University College London, investigating detection techniques for optical fiber gyroscopes.