Phase-reading, all-fiber-optic gyroscope

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An open-loop, all-fiber-optic gyroscope with wide dynamic range and linear scale factor is described. This novel approach converts the Sagnac phase shift into a phase shift in a low-frequency electronic signal by using optical phase modulation followed by amplitude modulation of the electronic signal. Preliminary experimental results verify the theoretical predictions.

Since the first demonstration of an optical-fiber Sagnac interferometer,¹ considerable effort has been devoted to fiber-optic gyroscopes. Some of the reported gyroscopes showed high sensitivity and good stability near zero rotation rate.²⁻⁴ Others have closed-loop configurations to overcome the limited dynamic range that stems from the nonlinear response of the interferometer to the rotation rate.⁵⁻⁶ However, problems in designing suitable electronic/optical feedback devices have made it difficult to achieve the high sensitivity shown in Refs. 2–4 in a closed-loop form.

Recently, we reported a series of simple, closed-loop approaches to large dynamic range using phase modulators as feedback devices.⁷⁻⁹ One advantage of these approaches is the availability of an in-line fiber-optic phase modulator that does not compromise the established high rotation sensitivity reported in Refs. 2 and 3. Also, a linearized scale factor with suppression of the source wavelength dependence, which is a problem with other approaches, is achieved.⁹ However, the output is in analog form, and digital readout over the full dynamic range with high resolution has not been demonstrated.

Other approaches to the dynamic-range problem include electronic signal processing¹⁰ and single-sideband detection¹¹ applied to open-loop gyroscopes. In the former case, dynamic range and resolution are limited by the analog-to-digital converter available, whereas the single-sideband approach requires a wideband phase modulator, which is not available in fiber-optic form at present.

In this Letter, we report an alternative signal-processing approach applied to an open-loop gyroscope, requiring no new components and capable of digital readout over unlimited linear dynamic range. Compared to so-called synthetic heterodyne demodulation procedures for two-beam interferometers, which have been described,¹²,¹³ the amplitude modulation used in the present scheme provides a simpler mechanism for achieving the desired form of output signal. It also provides a complementary pair of output signals, permitting direct demodulation by means of a standard time-interval counter, giving digital readout with essentially unlimited dynamic range.

Rotation introduces a nonreciprocal phase shift (Δφ_R) between the counterpropagating waves in an optical-fiber Sagnac interferometer. In most cases, this phase information is converted into intensity information through an optical interference process. Although the differential phase shift (Δφ_m) is linearly proportional to the rotation rate, the intensity output is a nonlinear (periodic) function of rotation rate. The key to obtaining a wide, linear dynamic range is to recover the original optical phase information.

The detector output I from a phase-modulated, open-loop gyroscope¹⁴ contains frequency components at the phase-modulation frequency f_m and its harmonics:

\[ I(t) = C[1 + \cos(\Delta\phi_m \sin \omega_m t - \Delta\phi_R)] \]

\[ = C \left[1 + \sum_{n=1}^{\infty} J_{2n}(\Delta\phi_m) \cos 2n\omega_m t \right] \times \cos(\Delta\phi_R) \]

\[ + \left[2 \sum_{n=1}^{\infty} J_{2n-1}(\Delta\phi_m) \sin(2n-1)\omega_m t \right] \times \sin(\Delta\phi_R). \]  

(1)

Here C is a constant, J_n denotes the nth-order Bessel function, Δφ_m is the amplitude of the phase difference between the counterpropagating waves produced by the modulation, and \( \omega_m = 2\pi f_m \). Note that if we have two sinusoidal signals at the same frequency \( n\omega_m \), whose amplitudes are \( \cos \Delta\phi_R \) and \( \sin \Delta\phi_R \), respectively, and whose phases are in quadrature, we can add them directly to obtain a single sinusoidal signal whose phase is \( \Delta\phi_R \). We see from Eq. (1) that the detector current contains terms of the above kinds, lacking only in that the cos \( \Delta\phi_R \) and sin \( \Delta\phi_R \) terms are of different frequencies. If the current I is amplitude modulated at the difference frequency \( \omega_m \) between adjacent harmonics, each harmonic component becomes partially translated into the frequencies of its nearest neighbors. The result is that all harmonics then contain terms in both cos \( \Delta\phi_R \) and sin \( \Delta\phi_R \) such that the nth harmonic has a term cos \( n\omega_m + \Delta\phi_R \). Here the Sagnac optical phase shift \( \Delta\phi_R \) has been transposed to a low-frequency electronic phase shift, which can be measured directly by standard means.

One simple way to realize the above approach is de-
If \( K_1 = K_2 = K \), Eqs. (3) become
\[
I_1 = K \cos(2\omega_m t - \Delta \phi_R),
\]
\[
I_2 = K \cos(2\omega_m t + \Delta \phi_R). \tag{4}
\]

Here a measurement of the phase difference between \( I_1 \) and \( I_2 \) yields \( 2\Delta \phi_R \). This method, which requires a double pole switch, has advantages in terms of stability over the simpler procedure of using a single detector channel modulated by a standard gate and measuring the phase of the first harmonic \((n = 1)\) against that of the signal applied to the phase modulator in the sensing coil used as a reference.

An experiment has been performed using an all-fiber gyroscope described earlier,\(^3\) as depicted in Fig. 1. An in-line phase modulator, which is a piezoelectric cylinder with several turns of fiber wrapped around it, was driven by a sinusoidal electronic signal at 13 kHz. An electronic switch was operated at 13 kHz in synchronism with the phase-modulation signal. Spurious signals resulting from switching transients are smaller at the even harmonics of the detector current than at the odd harmonics. For this reason we chose to operate at the second harmonic of the detector output, corresponding to Eqs. (4). Signals at 26 kHz were selected from channels 1 and 2 by using two bandpass filters and sent to a digital time-interval counter, which measured the time difference between zero crossings in the two channels.

The condition \( K_1 = K_2 \) in Eqs. (3) was achieved ex-
In summary, an approach to a wide dynamic range has been introduced that is applied directly to a standard all-fiber gyroscope without any additional optical elements, yielding a scale factor that is strictly linear in principle and digital output. The stability of the scale factor will depend on the stabilities achievable in the phase and amplitude modulators, filters, and other electronic components and is now under study.

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References