Triangular phase-modulation approach to an open-loop fiber-optic gyroscope

Pie-Yau Chien and Ci-Ling Pan

Institute of Electro-Optical Engineering, National Chiao-Tung University, Hsinchu, Taiwan 30050, China

Lih-Wuu Chang

Chung-Shan Institute of Science and Technology, Longtan, Taiwan, China

Received June 25, 1991

A new approach to an open-loop, all-fiber gyroscope with a wide dynamic range and a linear scale factor is described. For signal processing, the Sagnac phase shift is converted into a phase shift in the low-frequency electrical signal by using a triangular phase-modulation waveform followed by gate switching. The basic principle of this technique and experimental results are reported.

In the early stage of the development of fiber-optic gyroscopes (FOG's), fundamental problems such as sensitivity and bias stability were solved by using light sources with short coherence lengths, e.g., superluminescent laser diodes[1-3] and polarization-maintaining fibers.[4,5] A noise-equivalent rotation rate of approximately $0.1°\,h^{-1}\,Hz^{1/2}$ was achieved. Later, various signal-processing schemes[6-18] were developed to realize FOG's with a linear scale factor, a wide dynamic range, and immunity to fluctuations in light intensity. There are two primary approaches to signal processing for FOG's. In open-loop FOG's, a sinusoidal phase modulator that utilizes the elasto-optic effect with lock-in detection is often used.[6] Alternatively, the optical phase is transformed into the phase shift of a low-frequency electrical carrier by the pseudoheterodyne scheme or the phase-modulated single-sideband detection scheme.[7-12] By using a deep phase-modulation index with the gyroscope, we have alleviated the amplitude-stability requirement in the pseudoheterodyne scheme.[11] In the closed-loop configuration, FOG's employ nonreciprocal phase shift devices in a feedback loop to compensate for the Sagnac phase shift. Faraday rotators,[13] acousto-optic modulators,[13] integrated-optic serrodyne modulators,[14,15] and gate phase modulators[16-18] have been used as nonrecipocal devices. In the future, if the cost and coupling loss in the integrated-optic device can be improved, the use of an integrated-optic phase modulator in either the open-loop or closed-loop configuration may be the most promising approach. One of the advantages of the integrated-optic phase modulators over the piezoelectric transducer is that the frequency response of the integrated-optic phase modulator is much higher than that of the piezoelectric transducer phase modulator. Thus a different type of phase-modulation waveform, not limited by the sinusoidal, can be added to the integrated-optic phase modulator to implement a different signal processing that is superior to the sinusoidal waveform. In this Letter we demonstrate a new signal processing for open-loop FOG's. It is achieved by applying a triangular modulation waveform to an integrated-optic-type phase modulator employed in the FOG. With this method, one need not stabilize the amplitude of the modulation signal as required by the pseudoheterodyne technique. The Sagnac phase shift is derived from the phase of the low-frequency electrical signal.

The basic operating principle of our method is as follows: Rotation of the gyroscope creates an unbalanced Sagnac phase shift of $\Delta\phi_R$ between counterprogating beams. The phase shift is proportional to the rotation rate. A triangular waveform, which can be considered as a dual-slope sawtooth waveform, is employed as the phase-modulation signal. The detected photocurrent $I(t)$ of an open-loop gyroscope can then be expressed as

$$I(t) = C\{1 + \cos[\phi(t) - \phi(t-\tau) + \Delta\phi_R]\}, \qquad (1)$$

where C is a constant, τ is the time delay of the fiber loop, and $\phi(t)$ is the triangular waveform, which can be expressed as

$$\phi(t) = +\alpha t \qquad \text{for } -T_s/2 < t < 0 \qquad (2a)$$

$$= -\alpha t \qquad \text{for } 0 < t < +T_s/2. \qquad (2b)$$

Here α is the rate change of the phase modulator and T_s is the period of the triangular waveform. If the period of the triangular waveform T_s is selected such that $\tau = T_s/2$, then the time-delay phase-modulation effect $\phi(t)_{\text{eff}} = \phi(t) - \phi(t-\tau)$ in the FOG can be written as $\phi_{\text{eff}} = 2\phi(t) = \pm 2\alpha t$. The polarization of $\phi_{\text{eff}}(t)$ corresponds to the different slope of the triangular waveform. If the peak phase deviation of the triangular waveform is larger than π rad, we can consider that the interferometric signal is scanned and a beat frequency is generated. The output signal can be rewritten as

$$I_1(t) = C\cos(\omega_{\text{eff}}t + \Delta\phi_R), \qquad -T_s/2 < t < 0, \qquad (3a)$$

0146-9592/91/211701-03$5.00/0

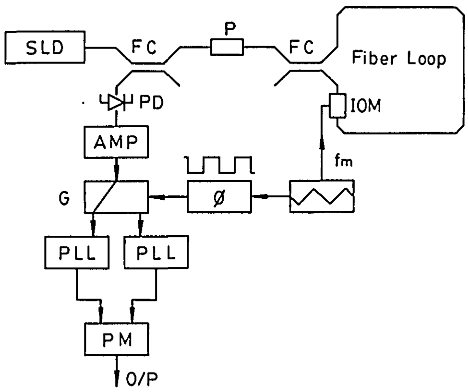

Fig. 1. Block diagram of the experimental setup. SLD, superluminescent diodes; FC's, fiber couplers; P, polarizer; IOM, integrated-optic phase modulator; ϕ, phase shifter; PD, photodetector; AMP, amplifier; G, gate switch; PLL's, phase-locked loop circuits; PM, phasemeter; O/P, output.

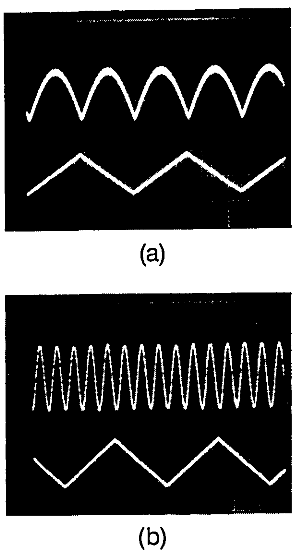

Fig. 2. Signal outputs of the experiment. Lower traces, modulation waveform; upper traces, the output signal at the photodetector. (a) Peak phase deviation is $\pi/2$, (b) peak phase deviation is 6π.

$$I_2(t) = C\cos(\omega_{\text{eff}}t - \Delta\phi_R), \qquad 0 < t < +T_s/2, \quad (3b)$$

where ω_{eff} depends on the slope change α of the triangular waveform. The signals of $I_1(t)$ and $I_2(t)$ are then selected separately by a square signal that is synchronized to the triangular waveform. When the output signal is selected, the output of the gating signal is considered to be multiplied by one. If the output signal is rejected, the signal is considered to be multiplied by zero. Thus the signals $I_1(t)$ and $I_2(t)$ after the gate-switching signal with the full period of the time scale are denoted $I_{1G}(t)$ and $I_{2G}(t)$, and they can be expressed as

$$I_{1G}(t) = C\cos(\omega_{\text{eff}}t + \Delta\phi_R)(1/2 + 2/\pi \sin\omega_s t + 1/3\sin 3\omega_s t + 1/5\sin 5\omega_s t + \ldots), \quad -T_s/2 < t < T_s/2, \quad (4a)$$

$$I_{2G}(t) = C\cos(\omega_{\text{eff}}t - \Delta\phi_R)(1/2 + 2/\pi \sin\omega_s t + 1/3\sin\omega_s t + 1/5\sin 5\omega_s t + \ldots), \quad -T_s/2 < t < T_s/2. \quad (4b)$$

From Eqs. (4a) and (4b), the Sagnac phase shift $\Delta\phi_R$ can be excited in the frequencies of $\omega_{\text{eff}} \pm n\omega_s$, where $n = 0, 1, 3, 5, \ldots$. The output signal with the same form as that in Eq. (3) but with the full period can be obtained by using the bandpass filter at ω_{eff}. A phase difference of $2\phi_R$ between $I_{1G}(t)$ and $I_{2G}(t)$ thus can be obtained.

The limitation of the modulation index and the synchronized gate-switching signal on this approach are discussed in what follows.

If the modulation index of the triangular waveform is adjusted such that $\omega_{\text{eff}} = n\omega_s$ (n is an integer), then the frequency difference between two most adjacent frequencies $\omega_{\text{eff}-1}$ and $\omega_{\text{eff}+1}$ and the signal frequency ω_{eff} is $|\omega_{\text{eff}-1} - \omega_{\text{eff}}| = \omega_s$. When the modulation index is adjusted such that $\omega_{\text{eff}} \neq n\omega_s$, then the frequency difference of $|\omega_{\text{eff}+1} - \omega_{\text{eff}}| > \omega_s$ (or $<\omega_s$) and $|\omega_{\text{eff}-1} - \omega_{\text{eff}}| < \omega_s$ (or $>\omega_s$) will be excited simultaneously, the requirement of the Q value of the bandpass filter to select the output signal being more critical in this case than in the case of $\omega_{\text{eff}} = n\omega_s$. Thus the specification of the bandpass filter (or the phase-locked-loop circuit) is influenced by the modulation index of the triangular waveform; this effect can be solved by designing the bandpass filter or the phase-locked-loop circuit properly, but it is not so critical as in the synthetic heterodyne detection method.[7-12] If the adjacent frequency components are included in the signal frequency, then the linearity that is characteristic of the phase detection of the phasemeter will be decreased.

If the phase delay between the gate-switching signal and the detector output is not adjusted to select the beat signals $I_1(t)$ and $I_2(t)$ properly, then these two signals cannot be separated, and Eqs. (4a) and

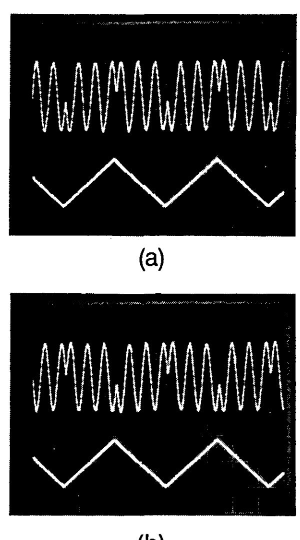

Fig. 3. Experimental results of the output signal at the photodetector for the direction opposite that of the rotation. (a) $\Delta\phi_R$ is negative, (b) $\Delta\phi_R$ is positive.

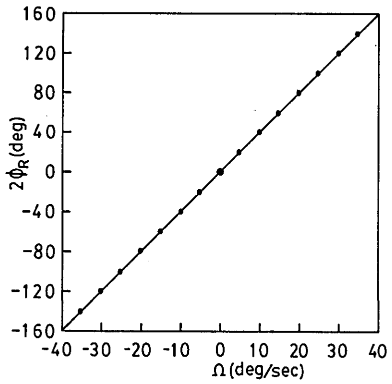

Fig. 4. Experimental results of the phasemeter output as a function of the rotation rate.

(4b) used in this method for signal detection are incorrect. In order to eliminate this problem, the gate-switching signal must be confined such that the cross talk between $I_1(t)$ and $I_2(t)$ will not occur. This can be implemented by decreasing the pulse width of the gate-switching signal such that $\tau < T_s/2$, where τ is the pulse width of the gate-switching signal.

A block diagram of the experimental setup of our FOG is shown in Fig. 1. Normally 3-dB fiber couplers are used. The gyroscope was formed by using polarization-maintaining fiber coils 15 cm in diameter. The fiber length was selected such that the scale factor of our gyroscope was $\Delta\phi_R = 2.0\Omega$, where Ω is the rotation rate of the gyroscope. A superluminescent laser diode (Laser Diode Model SRD-8302-PPF) was employed as the light source to reduce noise. An integrated-optic phase modulator placed at the end of the fiber loop was used as the phase modulator. A triangular waveform was applied to the integrated-optic phase modulator, and its frequency was adjusted such that the condition $T_s = 2\tau$ was satisfied. Figures 2(a) and 2(b) show that the applied modulation waveform and the detector output of the gyroscope under the peak phase deviation were $\pi/2$ and 6π separately. The output signals under a different direction of rotation rate are shown in Fig. 3. It was shown that the Sagnac phase shift was included in the phase of the beat frequency ω_{eff}, as shown in Eqs. (3). The output signal of the gyroscope was then gate switched by an analog switch that was synchronized to the triangular waveform. The two gated signals were fed into separate channels followed by bandpass filters at ω_s, constructed using the phase-locked-loop circuits for signal demodulation. A phase difference of $2\phi_R$ was measured by the phasemeter. Figure 4 shows the measured phase shift at the output of the phasemeter as a function of the rotation rate of the FOG. The experimental results showed that a good linearity over a wide dynamic range was obtained.

In summary, a novel signal-processing method based on triangular-waveform-modulated open-loop operation of a FOG has been demonstrated. The FOG exhibits a wide dynamic range with a linear scale factor. The limitation on the pseudoheterodyne signal processing by using the sinusoidal waveform is now eliminated by this technique. This technique can also be applied to the other optical fiber sensor system.

This research was partially supported by the National Science Council of the Republic of China and the Chung-Shan Institute of Science and Technology.

References

1. H. C. Lefevre, R. A. Bergh, and H. J. Shaw, Opt. Lett. **7,** 454 (1982).
2. W. K. Burn, C. L. Chen, and R. P. Moeller, IEEE J. Lightwave Technol. **LT-1,** 98 (1983).
3. W. K. Burn and R. P. Moeller, IEEE J. Lightwave Technol. **LT-1,** 381 (1983).
4. W. K. Burn, R. P. Moeller, C. A. Villarruel, and M. Abebe, Opt. Lett. **8,** 540 (1983).
5. R. A. Bergh, H. C. Lefevre, and H. J. Shaw, Opt. Lett. **6,** 502 (1981).
6. K. Bohm, P. Marten, K. Petermann, and E. Weidel, Electron. Lett. **19,** 997 (1983).
7. A. D. Kersey, A. C. Lewin, and D. A. Jackson, Electron. Lett. **20,** 368 (1984).
8. B. Y. Kim and H. J. Shaw, Opt. Lett. **9,** 378 (1984).
9. D. Eberhard and E. Voges, Opt. Lett. **9,** 22 (1984).
10. M. Oh and Y. Kim, Opt. Lett. **13,** 521 (1988).
11. P. Y. Chien and C. L. Pan, IEEE Photon. Technol. Lett. **3,** 284 (1991).
12. K. Ono, Y. Nishiura, and M. Nishikawa, Appl. Opt. **30,** 1070 (1991).
13. W. C. Davies, W. L. Pondrom, and D. E. Thompson, in *Fiber-Optic Rotation Sensors and Related Technologies,* S. Ezekel and H. J. Arditty, eds. (Springer-Verlag, New York, 1982), pp. 308–315.
14. J. L. Davis and S. Ezekiel, Opt. Lett. **6,** 505 (1981).
15. A. Ebberg and G. Schiffner, Opt. Lett. **10,** 300 (1985).
16. C. J. Kay, Inst. Electr. Eng. Proc. **132,** 259 (1985).
17. B. Y. Kim and H. J. Shaw, Opt. Lett. **9,** 263 (1984).
18. B. Y. Kim and H. J. Shaw, Opt. Lett. **9,** 375 (1984).