Fiber-optic gyroscopes based on polarization scrambling

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A novel fiber-optic gyroscope with a single-mode diode laser as the light source and two polarization scramblers as time-varying depolarizers is demonstrated. This arrangement reduces the nonreciprocal phase noise induced by the cross coupling between polarization modes in single-mode fibers. The experimental results show that a phase-noise reduction factor of 18 can be achieved.

The stability of the output signal of fiber-optic gyroscopes (FOG's) is seriously affected by the sensitivity of the polarization state of the light guided in the fiber to the environment. Cross coupling between polarization modes in single-mode optical fibers gives rise to a nonreciprocal phase shift between the counterpropagating beams in the Sagnac loop. These phase shifts cannot be distinguished from rotation-induced phase shifts and produce unpredictable changes in the output signal. True single-mode operation, with an ideal polarization filter at the common input/output port, eliminates such errors.[1] The usefulness of this approach is, however, limited in practice by the finite extinction ratio of polarizers.[2,3] Broadband sources such as superluminescent diodes (SLD's) with depolarizers and polarization-maintaining fibers are commonly used to solve this problem.[4–6] A SLD with a birefringence modulator has been reported to reduce the phase noise of a FOG to 0.01°/h.[7] The SLD, however, has some disadvantages, e.g., a short lifetime because it operates at a current much above the threshold current, a low output power, and a low coupling efficiency into a single-mode fiber. It is also rather expensive since demand for the SLD for other applications is limited. By using the polarization-maintaining fiber for the sensing loop, one must also align either of the optical axes with the polarization of the incident light. Optical components based on the polarization-maintaining fiber are also currently much more expensive than non-polarization-maintaining single-mode fiber devices. For the middle-to-low sensitivity regime a low-cost and easily implemented FOG that uses a laser diode as the light source, with single-mode-fiber-based optical components and a single-mode fiber in the sensing loop, is desirable. In this Letter we report the underlying concepts and operating characteristics of such a FOG. The phase noise is greatly reduced by employing two polarization scramblers as time-varying depolarizers in the FOG. To our knowledge, this is the first use of such devices in FOG's.

A schematic of our experimental setup is shown in Fig. 1. The laser diode used in our research was a single-mode device (Hitachi HLP-1400). Its operating temperature and driving current were both stabilized. A small-current modulation signal of 1 MHz

was applied to the laser diode to increase the spectral width of the laser diode to approximately 300 MHz. This was measured with a Fabry–Perot interferometer. The optical coupler and the sensor loop were made of non-polarization-maintaining single-mode fibers. Two polarization scramblers, PS1 and PS2, were fabricated by coiling a short length of fiber into a loop. They were then each fixed to the cone of a loudspeaker, which could be forced to vibrate. This caused mainly periodic variations in the birefringence of the single-mode fiber. Thus the polarization of light in the fiber was modulated.[8] The performance of the scramblers was examined as follows: The light from a power-stabilized laser diode was coupled into the scrambler. A polarizer was placed at the output port of the device. By adjusting the polarization state fed into the scrambler with a polarization controller and the amplitude of the modulation signal to the loudspeaker, we could observe whether an amplitude-modulated light output contained harmonic terms of the modulation frequency. This characteristic indicated whether the polarization state of light was modulated by the scrambler. The first polarization scrambler (PS1), placed in front of the fiber coupler, was used for prescrambling the input polarization state to the fiber coupler. As a result, the polarization-state-dependent phase noise induced by the fiber
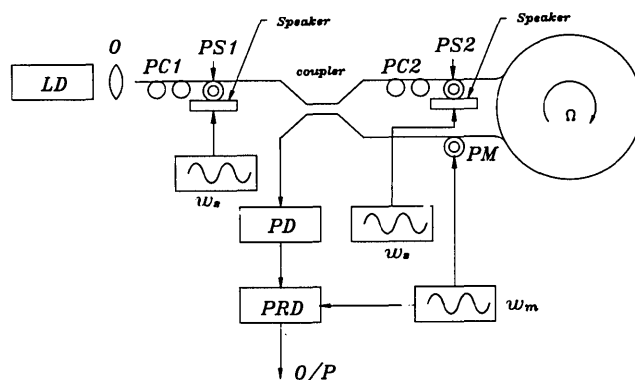

Fig. 1. Experimental setup of the FOG based on polarization scrambling. LD, laser diode; PM, phase modulator; PD, photodetector; PRD, phase-reading-detection circuit; O, objective lens; O/P, output.
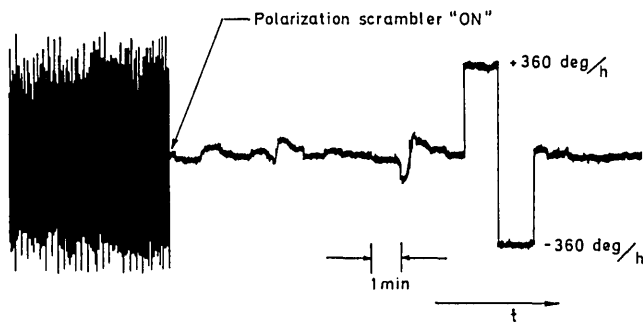
Fig. 2. Recorder trace of the output phase signal of the gyroscope with and without the polarization scrambler.

coupler was reduced. The second polarization scrambler (PS2), placed in the sensing loop, was used to scramble the polarization-state-coupling phase noise induced by mode coupling in the fiber loop. Finally, two polarization controllers, PC1 and PC2, were placed before the polarization scramblers and were used to adjust the input polarization state to the polarization scrambler, such that the polarization states were scrambled (modulated). In order to examine reduction in the phase noise in the gyroscope due to the scramblers, we did not employ polarization filtering at the input/output port in our experiment.

The fiber length was selected such that the scale factor of our gyroscope was $\Delta\phi_R = 2.0\Omega$, where $\Delta\Omega_R$ is the Sagnac phase shift and Ω is the rotation rate of the gyroscope. An in-line piezoelectric transducer with several turns of fiber wrapped around it was used as the phase modulator. Two independent sinuosidal wave forms of 200 Hz were applied to the loudspeakers. This frequency was much higher than our measurement bandwidth of 1 Hz; thus the phase signal in the 200-Hz wave form could be effectively extracted. The amplitude of the wave form was adjusted such that an induced intensity-modulation depth of 50% was detected. A 40-kHz sinusoidal wave form was applied to the piezoelectric transducer for signal processing. The amplitude of the modulation wave form was adjusted to implement the so-called phase-reading detection scheme.[9] In this case the output signal of the photodetector can be expressed as

$$I(t) = I_0(t)\cos(2\omega_m t \pm \Delta\phi_R), \qquad (1)$$

where $I_0(t)$ includes the effect of the polarization-scrambler-induced intensity modulation on the incident laser intensity and ω_m is the applied phase-modulation signal to the piezoelectric transducer. From Eq. (1) one can see that the Sagnac phase signal $\Delta\phi_R$ is included in the phase term at the carrier frequency of $2\omega_m$ only. By using either the phase-locked loop technique or the zero-crossing comparator, the amplitude term $I_0(t)$ can be removed for the measurement of $\Delta\phi_R$.

It follows that by using this signal-detection method, the reciprocal phase signal and nonreciprocal phase signal can be distinguished. In our experiment the nonreciprocal phase signal $\Delta\phi_R$ is of interest to us. It can be demodulated simply by using a phase meter. Figure 2 shows the phase noise of the gyroscope with and without the polarization scramblers. It is clear that when the polarization scramblers are used the phase noise is reduced from 360°/h to 20°/h. This corresponds to a reduction factor in phase noise of 18. The drift of the Sagnac phase shift in Fig. 2 is due to the nonreciprocity configuration of the system. In other words, the extinction ratio requirement in this low-to-middle sensitivity FOG can be lowered by the same amount.

In summary, a novel method for phase-noise reduction in FOG's with a single-mode laser diode as the light source has been demonstrated by using two polarization scramblers. If a high-frequency current-modulation signal and polarization filtering are adopted, the phase noise of our system can be further reduced. An additional reduction in the phase noise can be achieved by employing a light source with a broader spectral width and a polarizer. The former can be achieved by deep current modulation of the laser diode.

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