# Scale-factor-stabilized fiber-optic gyroscope based on a spectrum-broadened laser-diode source

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A spectrum-broadened laser-diode source that uses the optical feedback and current-modulation effects has been adopted as the light source of a fiber-optic gyroscope to reduce the inherent phase noise. The scale factor of the gyroscope has also been stabilized.

The use of broadband sources such as superluminescent diodes (SLD's) in the fiber-optic gyroscopes[1–4] (FOG's) that utilize passive Sagnac interferometers has become popular because of the inherent reduction in noise due to Rayleigh backscattering, the polarization noise, and the bias offsets due to the nonlinear Kerr effect. The elimination of these noise sources has permitted the demonstration of passive interferometers that operate close to shot-noise limits and with good long-term stability. The use of the SLD in a FOG system is required in high-resolution gyroscopes. However, it has been known that the use of a SLD could present some disadvantages, namely, short lift time because it operates at a current much higher than that of a conventional laser diode, low power output, low coupling efficiency into a single-mode fiber, and rather high cost, since the demand for SLD's for other applications is limited. At high rotation rates the signal-to-noise ratio of a FOG with a SLD as the source will also be reduced because of the loss of fringe visibility owing to the limited coherence of the source. Thus in the medium-resolution gyroscopes with sensitivities of 1°/h to 10°/h the spectrally broadened laser diode is an attractive alternative as the light source. In this Letter we use a single-mode laser diode to replace the SLD. The spectral width of the laser diode was broadened by the optical feedback and current-modulation effects. By using this method, we demonstrate that the sensitivity of the FOG can be improved to the same order as one with a SLD source for medium-resolution applications. At the same time, the scale factor of the FOG has also been stabilized.

When a sinusoidal phase-modulation signal of $\phi_m \cos \omega_1 t$ is applied to the piezoelectric-type phase modulator at one end of the fiber sensing coil, the rotation-induced phase shift $\phi_R$ is converted into the amplitude term of the interference signal at the harmonics of the phase-modulation frequency $f_1$ ($\omega_1 = 2\pi f_1$). The output current in the photodetector at this frequency can be expressed as[5,6]

$$\begin{aligned} I_d(t) &\cong \gamma I_0(t)[1 + \cos(\eta \cos \omega_1 t - \phi_R)] \\ &\cong \gamma I_0(t) \left\{ 1 + \cos\phi_R \left[ J_0(\eta) + 2\sum_{k=1}^{\infty} J_{2k}(\eta) \sin 2k\omega_1 t \right] \right. \\ &\quad \left. + \sin\phi_R \left[ 2\sum_{k=1}^{\infty} J_{2k-1}(\eta) \sin(2k-1)\omega_1 t \right] \right\}, \end{aligned} \tag{1}$$

where $I_0(t)$ is the intensity of the light source and $\gamma$ is the visibility of the interferometer. The signal fading due to polarization-state fluctuations is included in $\gamma$. The factor $\eta$ is the modulation amplitude of the phase difference between the counterpropagating light beams and is defined as $\eta = 2\phi_m \sin(\omega_1\tau/2)$, where $\tau$ is the group delay of the fiber coil. Also in relation (1), $J_k(\eta)$ is a Bessel function of order $k$ and $\phi_R$ is the rotation-induced optical phase shift.

The intensity of the light source, $I_0(t)$, is modulated with a sinusoidal wave form that can be expressed as $(1 + K \cos \omega_2 t)$. The factor $K$ is the intensity-modulation depth of the intensity-modulated laser diode. Thus the signal output at harmonic frequencies of zero and first orders after $\omega_1$ at the photodetector can be expressed as

$$\begin{aligned} I_1(\omega_1 = 0, \omega_2) &\cong I_0(t)\gamma(1 + K\cos\omega_2 t) \\ &\quad \times [1 + J_0(\eta)\cos\phi_R], \end{aligned} \tag{2a}$$

$$\begin{aligned} I_2(\omega_1, \omega_2) &\cong I_0(t)\gamma(1 + K\cos\omega_2 t) \\ &\quad \times 2J_1(\eta)\sin\phi_R \sin\omega_1 t. \end{aligned} \tag{2b}$$

If the frequency $\omega_2$ is selected to be much larger than $\omega_1$, the amplitude-modulation term of $K \cos \omega_2 t$ in relation (2b) can be removed through the phase-sensitive detector (PSD) circuit followed by a low-pass filter. Thus the detected signal, $I_2(\omega_1, \omega_2)$, is the same as the output signal of the gyroscope without intensity modulation. As a result, the detection of the rotation rate of $\sin \phi_R$ in relation (2b) is not influenced by the intensity-modulation effect. This high-frequency intensity-modulation signal, however, can be used to broaden the spectral width of the laser diode. The output signal of relation (2a) is used for stabilization of the scale factor. This is implemented by adjusting the modulation index of the phase modulator such that the condition that $J_0(\eta) = 0$ is satisfied. The rotation-induced detection error of $J_0(\eta)\cos \phi_R$ in the scale factor can be easily detected by the PSD circuit at $\omega_2$. The adjustment of the phase-modulation index such that $J_0(\eta) = 0$ can be easily implemented by introducing a large change of rotation rate in the gyroscope.

An experiment was performed by using the setup as shown in Fig. 1. A 250-m length of ordinary single-mode fiber was wound on an aluminum disk with an average radius of 2.5 cm. A single-mode laser diode (Hitachi HLP-1400, λ = 0.83 μm) was used as the light

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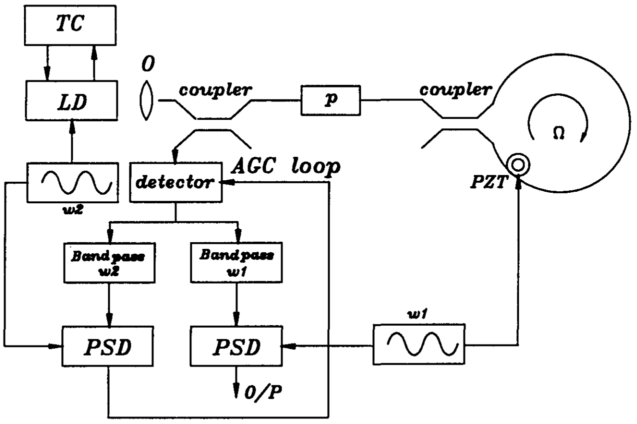

Fig. 1. Experimental setup of the open-loop FOG with a spectrum-broadened laser-diode source. LD, laser diode; O, objective lens; p, polarizer; PZT, piezoelectric transducer; TC, temperature controller; AGC, O/P output.

Fig. 2. Recorder trace of the phase noise when the spectrum of the laser diode (LD) is unbroadened and broadened.

source. The temperature of the laser diode was stabilized at 20 ± 0.005°C. The driving current of the laser diode was stabilized so that the change is less than 1 $\mu$A. The light reflected from the fiber end was used as the optical feedback light into the laser diode. By properly adjusting the driving current of the laser diode, a broadened spectral width of 30 GHz or 0.08 nm was obtained. This was measured with the Fabry–Perot interferometer. In our system, mode hopping was observed in certain ranges of the driving current of the laser diode. With proper selection of the operation current, mode hopping can be avoided. One region of the driving current of the laser diode that gives rise to a stable spectrum-broadened output was between 113 and 118 mA. In the experiment reported here, the laser diode was operated at 115 mA. By adding a sinusoidal current-modulation wave form of 10 mA at 100 kHz to the laser diode, the spectral width of the laser diode was further increased to 35 GHz. This current-modulation signal can also be used as the dither signal to eliminate the low-frequency-induced phase noise by the PSD circuit. The PSD output signal at the reference frequency, $f_1 = 30$ kHz, was used as the output signal of the gyroscope. A typical recorder trace is shown in Fig. 2. It shows that when the spectrum of the laser diode is unbroadened, a phase noise greater than 120°/h is present. When the spectrum of the laser diode is broadened and modulated, the phase noise is reduced to 10°/h. In comparison, when the same experimental condition is used except for replacing the laser diode with a SLD with a spectral width of 18 nm, we found that the phase noise was approximately 4°/h. This is of the same order as the FOG with a spectrally broadened laser-diode source. The bandwidth of the PSD in our experiment was selected to be 5 Hz.

When $J_0(\eta)$ was adjusted to zero, the scale factor of $\gamma I_0(t)$ was demodulated by the PSD circuit at $\omega_2$. This output signal was compared with a stable reference voltage and then went through a proportional and integrating compensating circuit to control the amplifier gain of the photodetector such that it was the same at $\omega_1$ and $\omega_2$. When the scale factor $\gamma I_0(t)$ detected at $\omega_2$ was stabilized, it was also stable at $\omega_1$. In order to simulate the variation in the scale factor, a polarization controller was added in the fiber loop to generate a variation of the visibility of the interferometer. Figures 3(a) and 3(b) show the recorder traces of the signal outputs of the PSD's at $\omega_1$ and $\omega_2$, respectively. A variable-gain controller within the two PSD circuits was used to adjust the detected output voltages at 1.5 V for $\omega_2$ and at 0.5 V for $\omega_1$. The rotation rate of the gyroscope in this experiment was 10°/s. Figure 3 demonstrates that there is a high degree of correlation between these two output signals. When the servo loop was closed, we were able to stabilize the ratio $\Delta[\gamma I_0(t)]/\gamma I_0(t)]$ such that its variation $\Delta[\gamma I_0(t)/\gamma I_0(t)] \leq 10^{-5}$.

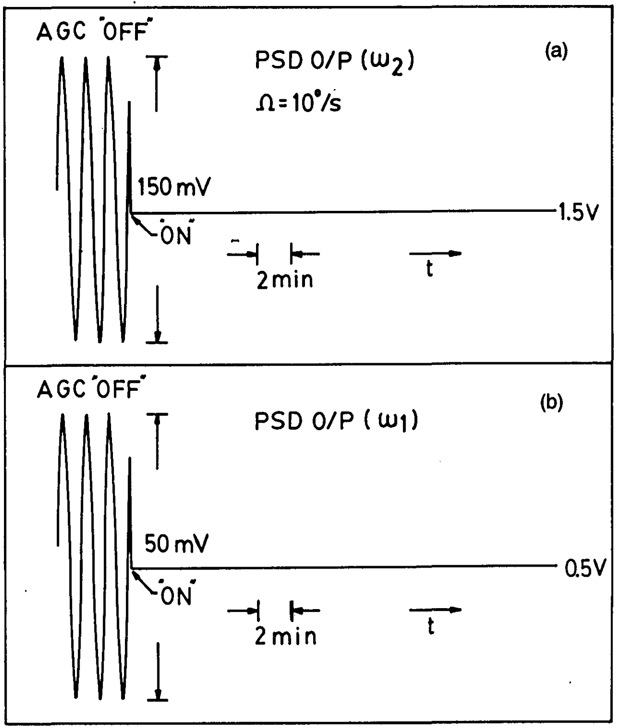

Fig. 3. Recorder trace of the scale factor stabilization loop for an open and closed loop. (a) The output signal is $I_1(\omega_1 = 0, \omega_2) = \gamma I_0(t)$ of the PSD at $\omega_2$. (b) The output signal is $I_2(\omega_1, \omega_2) = \gamma I_0(t) J_1(\eta) \sin \phi_R$ of the PSD at $\omega_1$.

In summary, a novel method to reduce the phase noise in the FOG system by using a spectrum-broadened laser-diode source was demonstrated. The scale factor was also stabilized by using the modulated light source. In comparison with the experiments performed with a SLD as the light source, the phase noise was found to be of the same order of magnitude in this medium-resolution FOG.

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