The novel stable control scheme of the light source power in the closed-loop fiber optic gyroscope

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Abstract. The light source power stability of the Fiber-Optic Gyroscope (FOG) affects directly the scale factor and bias stability of FOG. The typical control scheme of the light source power employs an additional photodetector to detect the output power of the light source. When the fiber loss of FOG varied due to the temperature change, the light power in the additional photodetector did not indicate this change, which decreased the control effect. The spike pulse overlapping on the gyro signal denotes potentially the change of the light power and fiber loss. In the novel scheme, the spike pulse is extracted from the gyro signal, and is transformed into the square wave by the differential circuit. According to the change of the square wave amplitude, FOG adjusts the bias current of the light source to keep the stable light power in the signal photodetector. It is a simple and low-cost scheme without an additional photodetector.

1. Introduction

FOG is a kind of the new type all-solid-state inertial instrument. The interferometric FOG (I-FOG) which is one kind of FOG has been already used in the traditional application fields of the gyros successfully \cite{1, 2}. The scale factor and bias stability of I-FOG is very important parameters for FOG performance \cite{3}, and the stability of the light source power affects directly these two parameters. So maintaining the light power stability is a vital way to enhance the gyro performance.

I-FOG uses generally the superluminescent diode (SLD). The major problem of this light source is its poor spectrum stability. The experiments showed that: SLD average wavelength drifts about 400ppm/K, and about 40ppm/mA with the bias current of the drive circuit \cite{2}. The traditional scheme employs the temperature control circuit and constant current source to keep the stable output power and average wavelength of SLD. At the same time, an additional photodetector, which is connected to the dead end of the fiber coupler in FOG (Figure 1), is employed to detect the change of the light source power. And then adjusting the output power of SLD is done by the feedback control circuit. But the light wave achieving to the signal photodetector and the other achieving to the additional photodetector are different in the light path, as shown in Figure 1. When the fiber loss of the optical components and fiber junctures varied due to the environmental temperature change, the light power achieving to the signal photodetector became unstable. The light signal in the additional photodetector did not indicate this change, which affected the control effect finally. Moreover, the traditional scheme is an expensive scheme for an additional photodetector.
Due to using the unsymmetrical phase modulating square wave in I-FOG, the spike pulses periodically overlap on the gyro signal [2], which are useless signals for I-FOG. However, these signals potentially indicate the change of the light source power and fiber loss. In the novel scheme, the spike pulses are periodically extracted from the gyro signal, and are transformed into the square wave signal by the differential circuit. The change of SLD output power is known by measuring the amplitude of the square wave, and then adjusting the light source power by regulating the output current of the constant current source to keep the stable light power in the signal photodetector.

2. The closed-loop I-FOG with the square wave biasing modulation

I-FOG is a kind of the inertial instrument based on Sagnac effect. When the gyro rotates, the light waves in the FOG produce interference, and then produce the Sagnac phase shift which is proportional to the rotation rate of the gyro [4]. The response to the rotation rate of the gyro is:

\[
P(t) = P_0 [1 + \cos(\Delta \phi_k)]
\]

Where \(P_0\) is the light source power; \(\Delta \phi_k\) is Sagnac phase shift. Equation (1) shows that the response is a raised cosine function, and symmetric about zero. At the zero point of the response, its slope is zero approximately. So when the gyro rotates slowly, the response is insensitive to the gyro rotation [2, 4].

To get high sensitivity, I-FOG employs the square wave biasing modulation technology so that I-FOG operates at the point with a non-zero response slope. A phase biasing modulation \(\phi_b\) is applied periodically in the positive and negative half-periods of the modulating square wave. The square wave half-period \(\tau\) is the time that the light wave spends on propagating a ring in the fiber coil, corresponding to the so-called eigen frequency \(f_p = 1/2\Delta \tau\) of the fiber coil [4]. The difference between the positive and negative modulating states is equal to \(\Delta P(\Delta \phi_k, \phi_b)\).

\[
\Delta P(\Delta \phi_k, \phi_b) = P_0 [1 + \cos(\Delta \phi_k - \phi_b)] - P_0 [1 + \cos(\Delta \phi_k + \phi_b)] = 2P_0 \sin \phi_b \sin \Delta \phi_k
\]

As \(\phi_b\) is equal to \(\pi/2\), the response to the gyro becomes a sine function with a stable zero point; while \(\Delta \phi_k\) is in the small range, \(\sin \Delta \phi_k \approx \Delta \phi_k\). So Equation (2) is simplified by Equation (3):

\[
\Delta P = 2P_0 \cdot \Delta \phi_k
\]

Hence the difference \(\Delta P\) between two modulating states is proportional to the rotation rate of the gyro.

However, the duty cycle of the modulating square wave is not absolutely equal to 1:1, which induces additional phase modulations. Within employing the unsymmetrical square wave modulation, the phase biasing modulation \(\phi_b\) has four modulating states [2]:

\[
\begin{align*}
+\phi_b & \quad t \in (1-\varepsilon)\Delta \tau \\
0 & \quad t \in \varepsilon \cdot \Delta \tau \\
-\phi_b & \quad t \in (1-\varepsilon)\Delta \tau \\
0 & \quad t \in \varepsilon \cdot \Delta \tau
\end{align*}
\]
Where $\epsilon$ is the error between the positive half-period and negative half-period of the square wave. During the time $\epsilon \cdot \Delta \tau$, the gyro output in the signal photodetector is as shown in Equation (1). Since the I-FOG employs the closed-loop control technology, $\Delta \phi_h$ is regarded as the error signal. So it is limited at zero [2, 5]. Hence the gyro output in $\epsilon \cdot \Delta \tau$ is:

$$P(t)=2P_0$$

(5)

Corresponding to the four states of the phase biasing modulation, there are four different values of gyro output. Here $\phi_i$ is equal to $\pi/2$.

$$P(t) = \begin{cases} 
P_0 \left[1 - \sin \Delta \phi_h \right] & t \in (1 - \epsilon) \cdot \Delta \tau \\
2P_0 & t \in \epsilon \cdot \Delta \tau \\
P_0 \left[1 + \sin \Delta \phi_h \right] & t \in (1 - \epsilon) \cdot \Delta \tau \\
2P_0 & t \in \epsilon \cdot \Delta \tau 
\end{cases}$$

(6)

So it can be seen that these spike pulses overlap on the gyro signal, whose the frequency is two times the square wave frequency. When the square wave frequency $f_m$ is equal to the eigen frequency $f_p$ of the fiber coil, the width of all spike pulses is equal to $\epsilon \cdot \Delta \tau$. If it not equal, one becomes wide and the other becomes thin, as shown in Figure 2 [2]. Equation (6) shows that: during the time $\epsilon \cdot \Delta \tau$, the spike pulse amplitude is proportional to the output power of the light source, which provides a simple way to detect the change of the light source power.

3. The novel stable control scheme of the light source power

Spike pulses and signals are same in the light route and reach the signal photodetector synchronously. So the change of spike pulses directly indicates the change of the light source power and fiber loss. Because the spike pulse amplitude is proportional to the light source power. Considering the fiber loss and the photodetector responsivity, so the signal which is detected in the signal photodetector is:

$$P_s(t) = 2 \times 10^{-4} \cdot K \cdot P_0$$

(7)

where $K$ is the photodetector responsivity and $L$ is the fiber loss. Therefore, the light power in the signal photodetector results from the amplitude of spike pulses. However, the operational amplifier in the circuit, which drives the Y wave-guide, has a limited slew rate, so it has shorter rise time $\Delta \tau_1$ and fall time $\Delta \tau_2$. Therefore the actual square wave of the phase biasing modulation is trapezoidal wave, as shown in Figure 3.

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Because the error $\varepsilon$ is a very small value, the responses to the trapezoidal wave modulation and fiber loss are the triangular waves instead of spike pulses, and the tip of the triangular wave directly reflects the change of the light source power and fiber loss in I-FOG. Because the modulating frequency is not absolutely equal to the eigen frequency, one spike pulse is wide and the other is thin, corresponding to two triangular waves that one is bigger and the other is smaller, as shown in Figure 4.

Due to the disturbance of the circuit noise, sampling the tip of the triangular wave is a difficult thing. In Figure 4, it can be seen that the changes of the light source power and fiber loss will induce the change of the triangular wave amplitude, and then affect the slope of the rising edge and falling edge of the triangular wave. In the novel scheme, these triangular waves are transformed into the square waves by the differential circuit which consists of the operational amplifier, resistance $R$ and capacitor $C$ (Figure 5), as shown in Figure 6.

The negative half-period amplitude $P_n$ of the square wave is shown in Equation (8), and the positive half-period amplitude $P_p$ is shown in Equation (9):

$$P_n = -RC \cdot \frac{d}{dt}(K_r \cdot t) = -\frac{RC \cdot P_t}{\Delta \tau_r} = -\frac{2 \times 10^{-10} KRC \cdot P_0}{\Delta \tau_r}$$  \hspace{1cm} (8)$$

$$P_p = -RC \cdot \frac{d}{dt}(-K_f \cdot t) = \frac{RC \cdot P_t}{\Delta \tau_f} = \frac{2 \times 10^{-10} KRC \cdot P_0}{\Delta \tau_f}$$  \hspace{1cm} (9)$$

Where $K_r$ and $K_f$ are the rising edge slope and the falling edge slope, $P_t$ is the amplitude of the triangular wave, $\Delta \tau_r$ and $\Delta \tau_f$ are the rising time and falling time of the triangular wave, which are calculated by the sampling period of the A/D converter: the sampling values are negative in the time $\Delta \tau_r$, and the sampling values are positive in the time $\Delta \tau_f$. So $\Delta \tau_f$ is equal to the product of the number of the negative values and the sampling period, and $\Delta \tau_f$ is calculated by the same way. Equation (8) and Equation (9) show that $P_n$ and $P_p$ are all proportional to the light source power $P_0$. Therefore the change of the light source power is known by measuring the amplitude of $P_n$ or $P_p$.

In the novel scheme, the bigger triangular wave is extracted from the gyro signal by the switch or multiplexer, and then it is transformed into the square wave by the differential circuit. According to the change of the square wave amplitude, FPGA adjusts the output current of the constant current source and keeps the stable light power in the signal photodetector. Moreover, the temperature control circuit is also employed in the novel scheme, which maintains the constant work temperature for the light source. The novel scheme is shown in Figure 8.
4. Simulation

In the simulation, the eigen frequency of the fiber coil is 100KHz, which induces the frequency 200KHz of the triangular wave. In general, the width of the triangular wave is from one-eighth to one-tenth of its period. So supposing that the rising time of the triangular wave is 0.3us, and the falling time is 0.325us; the photodetector responsivity $K$ is typically $8 \times 10^5$V/W, and RC 0.05us.

When the light source power changed, the square wave amplitude changed linearly (Figure 8). On the other hand, when the fiber loss in FOG increased due to the temperature change, the square wave amplitude decreased monotonously (Figure 9). The two figures showed that the square wave amplitude indicated directly the change of the light source power and the fiber loss in the I-FOG.

5. Conclusion

The spike pulses in the gyro signal could indicate the change of the light source power and fiber loss. The novel scheme makes use of this characteristic, and transforms the spike pulses into the square waves by the differential circuit. By measuring the square wave and adjusting the output current of the constant current source in I-FOG, the light power in the signal photodetector were kept at a stable value approximately. Comparing with the traditional scheme, it is a simple and low-cost scheme.

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