# Study on the Drift of Modulated Phase in Interference Fiber Optic Gyroscope

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Abstract-Integrated optical chip (IOC) is an essential component in the closed-loop interference fiber optic gyroscope(IFOG) system. One of the main functions of IOC in IFOG is to modulate the phase, which includes the  $\pi/2$ phase biased by square waves and Sagnac phase biased by ladder waves. In fact, both square waves and ladder waves have high frequency, including multiple harmonic waves and being disturbed easily, which induce the drift of modulated phase in IOC, and has great effect on IFOG performance, such as zero bias and drift. This paper analyzes theoretically the relationship between two kinds of modulated phases and the performance of IFOG drift, and searches for the error information in two kinds of modulated phases. Focusing on different error factors in IOC, the system is optimized in aspects of power source, clock, electromagnetic compatibility (EMC), signal processing and so on, to restrain phase drift error of  $2\pi$ , then to improve the bias stability of IFOG. Signals of the power source, clock, EMC, and signal processing and so on are tested, the test results show that all these methods are effective to restrain the drift of modulated phase in IOC, the system is stable and reliable. The static testing data of FOG is obtained in Three-axis Turntable, and the static testing data is analyzed quantitatively by using the method of Allan variance to identify random errors related to the drift of modulated phase from all kinds of error sources in the FOG system. The result is shown that the bias stability of the FOG system is better than 0.03°/hr. We also obtained the dynamic testing data of FOG in Three-axis Turntable, the result is shown that scale factor stability of the FOG system is better than 25ppm. To sum up, the whole performance of the IFOG system can meet the requirements of inertial navigation system (INS) with high precision.

*Index Terms*—Interference fiber optic gyroscope (IFOG), Bias stability, Modulated phase, Signal processing, Integrated optical chip (IOC)

# I. INTRODUCTION

Interference fiber optic gyroscope (IFOG) is a novel optical rotation sensor based on Sagnac effect. Inertial rotation is measured in IFOG as the phase difference between two lightwaves traveling in opposite direction around fiber-optic sensing loop. Modulated phase is used to compensate the phase of Sagnac effect in digital closed loop feedback system. The process of constructing digital closed loop is one of the key technologies in IFOG system, while, IOC is the critical component in the closed-loop IFOG system.

IOC in IFOG is a kind of annealed proton exchange LiNbO<sub>3</sub> waveguide, which has the functions of polarimeter, coupler and phase modulator. Adoption of the IOC in IFOG system can simplify structure, improve precision and enhance stability of IFOG.

The application of IOC in IFOG improves the stability of IFOG scale factor and expands the range of IFOG dynamic character. The drift character of modulated phase in IOC, such as accuracy, repetition, stability, and noise immunity, has great effect on IFOG performance of zero bias and drift. This article analyzes the drift character of modulated phase theoretically, and seeks for effective methods to restrain the error in real application.

## II. PRINCIPLE OF DIGITAL CLOSED-LOOP IFOG

The structure of digital closed-loop FOG is shown in figure 1. Square wave voltage is used to produce  $\pi/2$  phase shift, and ladder wave voltage is used to compensate Sagnac phase shift.



Figure 1. System structure of digital closed-loop FOG.

Interference signal phase in FOG is given by

$$\Delta \Phi = \Phi_s + \Phi_f + \Phi_I$$



Figure 2. Modulated phase of ladder waves in IOC.

Where  $\Phi_s$  is Sagnac phase shift in fiber coil;  $\Phi_f$  is

the phase produced by square wave;  $\Phi_J$  is the phase produced by ladder wave. Light intensity of interference signal in FOG is given by

$$I_1 = A[1 + \cos(\Phi_s + \Phi_f + \Phi_J)]$$

Light intensity of interference signal on square wave positive part is given by

$$I_{1} = A[1 + \cos(\Phi_{s} + \pi/2 + \Phi_{j})] = A[1 - \sin(\Phi_{s} + \Phi_{j})]$$
(1)

Light intensity of interference signal on square wave negative part is given by

$$I_2 = A[1 + \cos(\Phi_s - \pi/2 + \Phi_J)]$$
  
=  $A[1 + \sin(\Phi_s + \Phi_J)]$  (2)

Eq. (1) reduced by Eq. (2) becomes as

$$\Delta I = -2A\sin(\Phi_s + \Phi_J). \tag{3}$$

When  $\Phi_s = -\Phi_I$ ,  $\Delta I = 0$ .

The signal processing system controls the voltage amplitude of ladder wave by using  $\Delta I$  when  $\Delta I \neq 0$ , and ladder wave changes  $\Phi_J$  until  $\Phi_s + \Phi_J = 0$ . The phase increment modulated by ladder waves equals to Sagnac phase, but opposite in direction.

The period of square wave and ladder wave increment is  $2\tau$ ,  $\tau$  is determined by FOG coil length.

$$\tau = L/(c/n)$$

Where L is length of fiber coil, c is the speed of light wave, n is fiber refractive index.

Interference signal in photoelectric detector is zero in theory when closed-loop IFOG is hold still absolutely.

# III. CHARACTER OF MODULATED PHASE DRIFT ERROR IN IFOG

The modulation-phase function of IOC is based on crystal's electro-optic effect, that is, refractive index in crystal can be changed by external electric field, while refractive index's changing results in optic phase shifting. Closed-loop digital FOG builds feedback control by using IOC's phase modulating character. LiNbO<sub>3</sub> is a kind of 3m dot uniaxial crystal, and has big electro-optic index  $\gamma$ 33, refractive index elliptical equation is

$$\frac{x^2}{n_x^2} + \frac{y^2}{n_y^2} + \frac{z^2}{n_z^2} = 1$$

Where, x, y, z are three axis direction, optic-wave transmits along z axis. Ellipse refractive index along long axis is  $n_0$ , along short axis is  $n_e \cdot n_x$ ,  $n_y$ ,  $n_z$  are three axis refractive index, and  $n_x = n_y = n_0$ ,  $n_z = n_e$ . Refractive index along three axises can be changed by out electric field, while refractive index's changing results in optic phase shifting.

Refractive index variable along three axises changed by out electric field can be described as

$$\Delta n_{ij} = -\frac{n^3}{2} \begin{vmatrix} -\gamma_{22}E_y - \gamma_{13}E_z & \gamma_{12}E_x & \gamma_{5-1}E_x \\ \gamma_{22}E_x & \gamma_{22}E_x + \gamma_{13}E_z & \gamma_{51}E_y \\ \gamma_{51}E_x & \gamma_{51}E_y & \gamma_{33}E_y \end{vmatrix}$$

Linear electro-optic effect changes optic-wave phase by using diagonal matrix parameters 11, 22, 33. In IOC, refractive index variable along x direction is

$$\Delta n_e = \frac{n_e^3 \gamma_{33} V \Gamma}{2G}$$

Where  $\Gamma$  is the overlap between electric field and optic field,

$$\Gamma = \frac{G}{V} \iint E \left| E' \right|^2 dA$$

Where G is space between two electrodes, *E* is electric field, *E*' is well-proportioned optic field.

Voltage V and phase in IOC has the following connection

$$\Delta \phi = k \Delta n_e L = \frac{n_e^3 \gamma_{33} V L \Gamma \pi}{G \lambda} \,. \tag{4}$$

In practice, we must consider LiNbO<sub>3</sub> crystal structure, electric parameters, signal processing style, and adopt reasonable scheme to make IFOG system optimal.

To meet the demand of high precision IFOG, IOC must have the character of quick modulation responsibility, good modulation linearity, and wide bandwidth. Closed-loop IFOG modulates optic phase at fiber coil characteristic frequency. IOC has great bandwidth range of 240 Mhz to 640Mhz, which is enough to meet IFOG signal processing. However the character of square wave and ladder wave are influenced by fiber length, refractive index, performance of electronic component, and IOC's characters of distributed capacitance, load impedance matching, all these factors will change some parameters of square wave and ladder wave, such as period, duty cycle, falling time, rising time.

Phase in IOC is modulated by square wave and ladder wave. Relationship between drift of modulated phase in IOC and zero bias stability of IFOG is discussed as follows.

 $\pm \pi/2$  phase will be changed when half wave voltage changed by out environment,  $\Delta \Phi_f = \Phi_f - \pi/2$  where

 $\Delta \Phi_f$  is square wave error.

Light intensity of interference signal in FOG is given by

$$I = A[1 + \cos(\Phi_{s} + \Phi_{j} \pm \frac{\pi}{2} \pm (\Phi_{f} - \frac{\pi}{2}))]$$

Light intensity of interference signal on square wave positive part is given by

$$I_1 = A[1 - \sin(\Phi_s + \Phi_J + (\Phi_f - \frac{\pi}{2}))]$$

Light intensity of interference signal on square wave negative part is given by

$$I_2 = A[1 + \sin(\Phi_s + \Phi_J - (\Phi_f - \frac{\pi}{2}))]$$

We obtain Eq.(5)

$$\Delta I = I_2 - I_1$$
  
=  $A \Big[ \cos(\Phi_s + \Phi_J - \Phi_f) - \cos(\Phi_s + \Phi_J + \Phi_f) \Big].(5)$   
=  $2A\sin(\Phi_s + \Phi_J)\sin\Phi_f$ 

Eq.(5) shows that  $\Delta I = 0$  when  $\Phi_s = -\Phi_j$  or  $\Phi_f = 0$ , we know that  $\Phi_f \neq 0$ , so we can obtain Eq.(6)

$$\Phi_I = -\Phi_S \,. \tag{6}$$

As shown in Eq.(3), Eq.(6) shows that the drift of  $\pm \pi$  /2 biased phase has no effect on IFOG performance, the increment of ladder wave can measure accurately Sagnac phase indued by outer rotational motions.

Due to impact of the drift of the ladder wave because of the external factors, the phase of the ladder wave  $\Phi_j$  is changed to  $\Phi_j(1-\varepsilon_r)$ ,  $\varepsilon_r$  is the phase error coefficient of the reset of the ladder wave. The output of the Sagnac interferometer is given by

$$I = A[1 + \cos(\Phi_s + \Phi_J(1 - \varepsilon_r) \pm \frac{\pi}{2} \pm (\Phi_f - \frac{\pi}{2}))]$$

Light intensity of interference signal on square wave positive part is given by

$$I_1 = A[1 - \sin(\Phi_s + \Phi_J(1 - \varepsilon_r) + (\Phi_f - \frac{\pi}{2}))]$$

Light intensity of interference signal on square wave negative part is given by

$$I_{2} = A[1 + \sin(\Phi_{s} + \Phi_{J}(1 - \varepsilon_{r}) - (\Phi_{f} - \frac{\pi}{2}))]$$

$$\Delta I = I_2 - I_1$$
  
=  $A\cos(\Phi_s + \Phi_J(1 - \varepsilon_r) - \Phi_f)$   
 $- A\cos(\Phi_s + \Phi_J(1 - \varepsilon_r) + \Phi_f)$   
=  $2A\sin(\Phi_s + \Phi_J(1 - \varepsilon_r))\sin\Phi_f$  (7)

$$\Phi_J = -\Phi_S / (1 - \mathcal{E}_r) \,. \tag{8}$$

Because of the existence of the phase drift of the ladder wave, the phase feed back is not the real reflection of the phase shift of Sagnac, then the phase increment of the ladder wave and the rotational speed of the vector are not proportion relation, which will led to unstability of zero bias, non-linear and low repeatability of the scale factor. Additionally, temperature drift of the photoelectric devices has direct influence on the precision of the ladder wave and both of the phase of the non-ideal ladder wave and Phase 2  $\pi$  have influence on the precision of FOG system.

# IV. METHODS OF RESTRAINING THE DRIFT OF MODULATED PHASE IN IOC

The following methods to restrain the drift of modulated phase in IOC are discussed by combining with the practice project, which have guided of the development of high precision and high stability IFOG.

# *A.* Low ripple power with enough high precision and stability



The interference signal from digital closed-loop IFOG always is retained at zero point, so the light power checked by PIN is weak, the signal processing is to distill weak signal. A/D converter samples the weak signals in PIN, and transforms analog signal to digital signal. These digital signals are processed by FPGA and sent to D/A converter to transform digital signals to analog signals. Analog signals in A/D and D/A converters are influenced greatly by the power ripple noise. So it is essential to choose the power with high transition efficiency, low ripple, and high precision when designing the source. Meanwhile layout must be optimized and reasonable

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filtering must be chosen. Figure 3 indicates the characteristic of 5V DC source. The source ripple is below 1%, and the stability is good.

## B. Reduce drift and jitter of system clock

Clock jitter in time domain is manifested as phase noise in frequency domain. The total jitter curve is the basis for estimating the magnitude of  $R_j$  and  $D_j$ . Since the total jitter curve is derived directly from the real-time clock signals, its value is the most accurate representation of the jitter.

Total clock jitter  $(T_j)$  includes random jitter  $(R_j)$ and confirmable jitter  $(D_j)$ , and  $T_j = R_j + D_j$ 

Random Jitter belongs to unpredictable temporal noise, which distributes by random Gauss probability on theoretical. Confirmable Jitter comes from power/ground noise, which mainly comes from ground-bound effect, by which the stability of power is influenced. The frequency of system clock will be changed by the ground-bound effect. Besides, the crystal threshold voltage will be changed by the voltage drop, which influences outer crystal stability. Moreover, the discontinuous and unsuited interconnection resistance induces signal reflection, the reflected signal folds on the primary signal inducing the increase on scope, and the time of voltage transforming becomes longer. The system clock jitter can be brought by crystal's thermal noise, mechanism size noise and other resonator noises, all these factors will induce crystal frequency unstability.

Clock from outer crystal is the benchmark of entire digital closed-loop FOG signal processing, the accuracy and stability of crystal influence IFOG performance directly. The clock must be optimized, and the crystal periphery circuit must be designed reasonably to minimize the outer disturbance.



Figure 4. Character of crystal waves.

Figure 4 shows the clock waves of crystal with the frequency of 5Mhz. Total clock Jitter ( $T_J = 1.4$ ps) shows excellent properties of timing sequence reference in IFOG signal processing.

### C. Optimization of EMC design

The signal cross-talk, coupling noise and other similar electromagnetic interference factors can influence the electrical characteristics of electronic components, time

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sequence, signal integrity of electric circuit, and halfwave voltage of the optical components in FOG system, which will lead to non-reciprocity phase error fluctuate disorderly. The disorder non-reciprocity phase error results in unstable bias and unstable scale factor.

To restrain the influence of electromagnetic interference factors, EMC(Electromagnetic Compatibility) need to be considered which is to lower the interference caused by high-frequency signal, to separate from source of interference, to cut off the coupling path of the radiation signal; Additionally, other reasonable methods should be considered to separate digital ground from analog ground, to control the path of returning current, to reduce the area of current return, to increase the distance between high speed digital signal and analog signal, and to enhance IOC's self interference immunity.

# D. Improvement of signal processing style

As mentioned above, due to the existence of temperature drift and the aging of the electronics(D/A converter, operational amplifier and others related), the change of IOC' s half-wave voltage, the gain of the phase modulation channel will be changed, which will lead to the ladder phase drift and reset drift of  $2 \pi$ . Especially, reset drift of  $2 \pi$  has direct effects on system stability. As a result, some improvement can be done, such as: 1. To introduce the second closed-loop feedback, the system structure with two closed-loops is shown as Figure 5; 2. To introduce four-state signal processing technology, the system control time sequence of four-state signal is shown as Figure 6 and Figure 7.

Through comparing the sampling values of the detector signals before and after reset, the phase  $2\pi$  reset error signal is obtained, which can be used to compensate the voltage drift of the  $2\pi$  phase. The integration of the error signal is followed which is set as the input of the second D/A to change the gain of the phase feedback channel and to obtain the precision phase  $2\pi$ .

As the phase  $2\pi$  reset period of every ladder wave is long to the low-speed signal, the second closed-loop feedback can not recognize the drift of the phase  $2\pi$ voltage in time. Four-state signal processing technology is a optimized method based on the second colsed-loop feedback, the principle is illustrated as follows: it is to change the offset phase shift of  $\pm \pi/2$  and to use four various kinds of offset phase with the time sequence making corresponding change, so as to make a solution to the phase  $2\pi$  drift in the low-speed situation.

In the first closed-loop feedback, every period  $\tau$  produces a suitable phase ladder  $\Phi_J$  to restrain the Sagnac phase  $\Phi_S$ . In the second closed-loop feedback, it produces the control gain of the digital compensation signal to guarantee the precision of phase  $2 \pi$ .

Through subtracting of the sum of sample values of the second one quarter period and the third one quarter period and the sum of sample values of the first one quarter period and the forth one quarter period, the open-loop value is obtained and the value of the gain error is the subtraction of sample values every half period. Both of the closed-loop feedbacks produce the corresponding ladder wave and gain compensation to guarantee the phase drift of IOC will be compensated in time.

$$\varphi_{f}(t) = \begin{cases} \frac{\phi_{0}}{2} & 0 \leq t < \frac{\tau}{2} \\ a\frac{\phi_{0}}{2} & \frac{1}{2}\tau \leq t < \tau \\ -\frac{\phi_{0}}{2} & \tau \leq t < \frac{3}{2}\tau \\ -a\frac{\phi_{0}}{2} & \frac{3}{2}\tau \leq t < 2\tau \end{cases}$$
(9)

$$\phi_0 = \frac{2\pi}{a+1}, a = 2, 3, \cdots$$
 (10)

$$\Phi_{f}(t) = \begin{cases} \frac{\phi_{0}}{2} - \left(-\frac{\phi_{0}}{2}\right) = \phi_{0} & 0 \le t < \frac{\tau}{2} \\ a\frac{\phi_{0}}{2} - \left(-a\frac{\phi_{0}}{2}\right) = a\phi_{0} & \frac{1}{2}\tau \le t < \tau \\ -\frac{\phi_{0}}{2} - \frac{\phi_{0}}{2} = -\phi_{0} & \tau \le t < \frac{3}{2}\tau \\ -a\frac{\phi_{0}}{2} - a\frac{\phi_{0}}{2} = -a\phi_{0} & \frac{3}{2}\tau \le t < 2\tau \end{cases}$$
(11)



After the theoretical analysis of normalization to the optical wave signal in IFOG, signal noise ratio (SNR) of the system is given by

$$\left(\frac{S}{\sigma_{shot}}\right)_{\phi_0} = \frac{1}{N_F} \cdot \frac{\sin \phi_0}{2\left[\gamma_T + \sqrt{\gamma_P + \cos^2(\phi_0/2)}\right]}$$

where  $\sigma_{shot}$  is the shot noise,  $\gamma_T$  is normalized thermal noise,  $N_F$  is set as noise coefficient,  $\gamma_P$  is polarization coupling noise, in the situation of the strong polarization in FOG,  $\gamma_P \approx 0$ .

The values of bias phase  $\phi_0$  are set to  $2\pi/3$ ,  $\pi/2$ ,  $2\pi/5$ ,  $\pi/3$ , the test result shows that when  $\phi_0 = 2\pi/3$ , it can obtain the best performance.

Electro optic phase shift due to the bias voltage of the second closed-loop feedback's output is set as  $\varphi_f(t)$  when the time is t, then  $\Phi_f = \varphi_f(t) - \varphi_f(t+\tau)$ . When  $\phi_0 = 2\pi/3$ , the values of bias phase of every period are set to  $(2\pi/3, -2\pi/3, -2\pi/3, 2\pi/3)$ 



Figure 6. Four-state modulation wave.

. Sequential control in the four-state signal processing is shown in Figure 6 and Figure 7 to indicate the corresponding bias phase sequence in IOC.



Figure 7. Phase biased by four-state phase in IOC.

Assume that phase drift of IOC happened, then halfwave voltage was changed to  $1/(1+\delta)$ , where  $\delta$  is error coefficient. In one period of four-state modulation process, the interference signal strength of PIN is given by

$$I_{4-1} = A \Big[ 1 + \cos \Big( \Phi_s + (1+\delta) \Phi_J + (1+\delta) \Phi_f \Big) \Big].$$

$$I_{4-2} = A \Big[ 1 + \cos \Big( \Phi_s + (1+\delta) \Phi_J - (1+\delta) \Phi_f \Big) \Big].$$

$$I_{4-3} = A \Big[ 1 + \cos \Big( \Phi_s + (1+\delta) \Phi_J - (1+\delta) \Phi_f \Big) \Big].$$

$$I_{4-4} = A \Big[ 1 + \cos \Big( \Phi_s + (1+\delta) \Phi_J + (1+\delta) \Phi_f \Big) \Big].$$

In the first closed-loop feedback,  $\Phi_s + \Phi_j = 0$  is easily obtained, then through subtracting of the sum of sample values of the second one quarter period and the third one quarter period and the sum of sample values of the first one quarter period and the forth one quarter period, the open-loop value of IFOG can be obtained:

$$\Delta I_{14-23} = 2A \cdot \sin(\delta \cdot \Phi_J) \cdot \sin\left[(1+\delta)\Phi_f\right].$$
(12)

It shows that, when the feedback phase drift which can be reflected directly on the bias phase of the second closed-loop system happened, the compensation of feedback phase drift can be easily achieved by using the value of open-loop system  $\Delta I_{14-23}$ . With the bias wave and modulation and demodulation system working simultaneously, real-time compensation of phase drift can be achieved by using the second four state closed-loop signal processing system, which will improve the stability and reliability of the system.

## E. Selection standard of D/A converter and amplifier

There are two D/A converters in IFOG signal processing, the main functions can be described as the following: 1. In the first closed-loop system, D/A converter changes the digital ladder signal to analog ladder signal; 2. In the second closed-loop system, it mainly uses D/A converter to restrain the phase drift of IOC by controlling the gain of power amplifying device to produce the precision voltage of phase  $2 \pi$ . As the process of phase drift of IOC is very long, dynamic performance of the second D/A converter is not very important to the system, but it is important to guarantee: high resolution, low gain error and low nonlinearity error.

For fiber coil with length of one kilometer, the transit time  $\tau$  is  $\tau = 1000/(c/n) = 5us$ , c is the speed of light wave, n is fiber refractive index. The cycle of four-state bias wave is 10us, which is linearly amplified by operational amplifier. The operator amplifier must be chosen with low noise and distortion, wide bandwidth according to the modulation frequency. In fact, the chosen operational amplifier bandwidth is three times wide than the bandwidth of IFOG. And the rise time of operational amplifier must be considered.

# V. RESULTS OF KEY SIGNALS AND SYSTEM PERFORMANCE

In the system with two closed-loops, the fluctuation range of interference signals represents the phase drift error. Interference signals should be stable when system is stable under the ideal condition. The test waveform is shown on Figure 8.

In the static testing of FOG system, it is used the method of Allan variance to make evaluation of the whole performance of IFOG. The method of Allan variance can separate and recognize almost every kind of noises effectively, which can not only make a suitable evaluation of IFOG system, but also can estimate the effects of restraining the phase drift in IOC.

### A. Measure result of IFOG interference signals

Figure 8 shows that the linearity of the ladder wave is better than ever before, the interference signals before reset and after reset are stable, and equal to adjacent interference signals in voltage amplitude. The IFOG system with two closed loops is stable too.



Figure 8. Interference signal of IFOG at reset point.

### B. Analysis of IFOG performance

After preheated time of fifteen minutes, IFOG output data is sampled about 3900s with three-axis turntable. Upper curve of Figure 8 is the output angle rate of IFOG on earth. It is used the method of Allan variance to analyze and calibrate the performance of IFOG. The static test result shows that bias stability (BS) of IFOG is



Figure 9. Curve of IFOG performance analyzed by Allan variance.

better than 0.03°/hr.

# VI. CONCLUSIONS

Since our goal was the attainment of navigation grade performance we have focused on a closed-loop system with an integrated optics chip (IOC). The integrated optics technology enables fabrication of a phase modulator with sufficient bandwidth to implement various loop closure signal processing schemes necessary for linear scale factor behavior over a wide rate range. During the process of IFOG research, it focus on the characters of IOC and the influence on phase drift of IOC because of driver performance of bias square and feedback ladder wave in the digital closed-loop FOG system. The conclusions are as follows: 1. The bias square's phase drift will not led the FOG system to a lower performance; 2. The feedback ladder wave's phase drift is the direct cause of the scale factor error of the FOG system's output; 3. After introducing the second feedback system and optimizing the IOC's driving signal, the phase drift error of IOC is minimized and the bias stability and scale factor of IFOG system are improved; 4. The research on the characters of IOC's phase disrift has great significance on the development of the high precise FOG system.

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