

# Low cost, practical, all-digital open-loop fiber-optic gyroscope

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A novel all-digital scheme for open-loop fiber-optic gyroscope (FOG), where only two key points of output wave were digitized directly, has been proposed. A control equation, with which the modulation depth of PZT modulator is stable when setting the modulation depth as 4.35 and a calculation equation, with which the Sagnac phase can be worked out, are derived. A modulation depth control and an automatic correlation sampling and a gain control technology were induced. A photo-type FOG was made and tested. The good performance was achieved.

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The open loop fiber-optic gyroscope (FOG, shown in Fig. 1) is one of the cheap and most attractive gyroscopes and can be used widely in medium or low precision inertial system although the linearity and dynamic range are limited<sup>[1]</sup>. However, there are some errors due to variation of environment and analog device defects, such as direct coupling bias, gain nonlinearity and so on and optical defects, such as loss, polarization cross-talk, split ratio change etc. In order to solve these problems, many schemes, including digital and analog, have been presented<sup>[2,3]</sup> and almost all digital schemes reported before are based on the technology where the output waveform of FOG was digitized directly and the Sagnac phase was calculated with digital signal processing technology. Because the modulation frequency of FOG is high ( $10^4 - 10^5$  Hz) and the higher sampling rate ( $10^5 - 10^6$  Hz) is necessary, the good performance cannot be obtained without expensive A/D converter and data signal processor (DSP) chips and complex arithmetic. The all-digital scheme to be demonstrated following is based on the signal characteristic of open-loop FOG and can be realized easily with ordinary devices.

Figure 1 shows the "compact structure" open-loop FOG. When a sine modulation signal ( $V_m$  waveform in Fig. 2) is added to the phase modulator, the output from the detector can be written as

$$v_{\text{pin}} = k\{1 + \cos[\Delta\phi_s + \phi_m \sin(\omega_m t)]\}, \quad (1)$$

$$\phi_m = 2K_p V_m \sin \frac{\omega_m \tau}{2}, \quad (2)$$

where  $k$  is coefficient related with light intensity induced to detector and electric circuit gain,  $\Delta\phi_s$  is Sagnac phase shift,  $\phi_m$  is modulation depth,  $\omega_m$  is angular frequency of

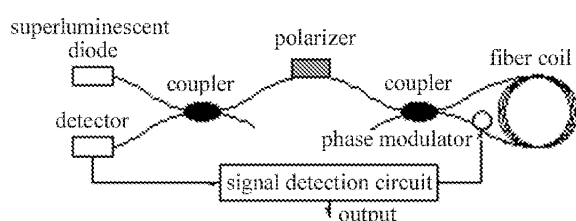


Fig. 1. "Compact structure" open-loop FOG.

modulation signal,  $K_p$  is modulation coefficient of modulator,  $V_m$  is amplitude of modulation wave, and  $\tau$  is time of light propagating in fiber coil once.

Using Bessel function to expand Eq. (1), the direct coupler (DC) component will be  $k(1 + J_0(\phi_m) \cos \Delta\phi_s)$ , where  $J_0$  is zero order of first kind Bessel function. Isolating DC component, the output signal (waveform  $V_o$  in Fig. 2) will be

$$V_o = k\{\cos[\Delta\phi_s + \phi_m \sin(\omega_m t)] - J_0(\phi_m) \cos \Delta\phi_s\}. \quad (3)$$

In Fig. 2, assume the times corresponding to the positive peak  $P$  and negative peak  $N$  of modulation waveform  $V_m$  as  $t_A$  and  $t_B$  respectively and the corresponding points in waveform  $V_o$  as  $A$  and  $B$ , and their values are  $V_{dA}$ ,  $V_{dB}$ . During a modulation period,  $V_{dA}$ ,  $V_{dB}$  will be

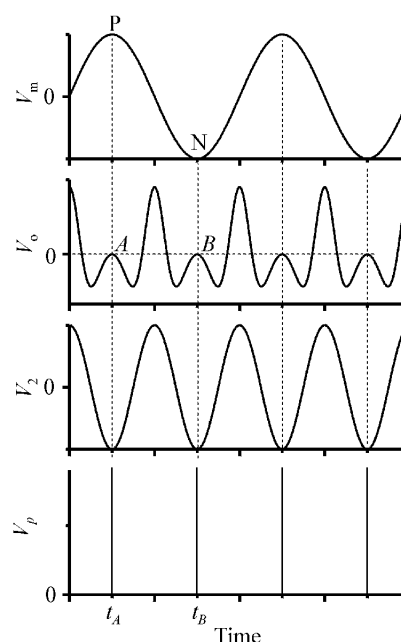


Fig. 2. Main waveforms in scheme.  $V_m$ : modulation waveform;  $V_o$ : output of detector without DC;  $V_2$ : the second harmonic component picked from output;  $V_p$ : trigger pulse generated from output.

$$V_{dA} = k\{\cos[\Delta\phi_s + \phi_m] - J_0(\phi_m) \cos \Delta\phi_s\}, \quad (4)$$

$$V_{dB} = k\{\cos[\Delta\phi_s - \phi_m] - J_0(\phi_m) \cos \Delta\phi_s\}. \quad (5)$$

It is obvious that the peak points *P* and *N* of modulation waveform  $V_m$  are always coincided with two utmost points *A* and *B* of waveform  $V_o$ . From Eqs. (4) and (5), we have

$$V_{dA} + V_{dB} = 2k[\cos \phi_m - J_0(\phi_m)] \cos \Delta\phi_s, \quad (6)$$

$$V_{dA} - V_{dB} = 2k \sin \phi_m \sin \Delta\phi_s. \quad (7)$$

So, given digitized values of  $V_{dA}$  and  $V_{dB}$ ,  $\phi_m$ ,  $\Delta\phi_s$  can be determined according to Eqs. (6) and (7). It is easy to digitize the two points with A/D conversion. However, Eqs. (6) and (7) form a transcendental equation group, it will take CPU long time to solve them. Herein, Eq. (6) was set to zero and taken as a control equation, Eq. (7) was taken as a calculation one. In general case  $\Delta\phi_s < 90^\circ$  and  $\cos(\Delta\phi_s) \neq 0$ , we can get a series solution of  $\phi_m$ :

$$\phi_m = 0, 4.35, \dots,$$

where 4.35 is the minimum nonzero solution. When  $\phi_m = 4.35$ , no matter how the Sagnac phase shift  $\Delta\phi_s$  changes, Eq. (6) will always be equal to zero. Conversely, we can use Eq. (6) to stabilize the modulation depth to 4.35. When  $\phi_m$  varies due to environment change, Eq. (6) will not be zero, then a error signal occurs and is taken as a feedback to adjust the value of  $\phi_m$  and keep it be 4.35. When  $\phi_m$  is set to 4.35 and  $V_{dA}$ ,  $V_{dB}$  are digitized with A/D converter,  $\Delta\phi_s$  can be calculated with Eq. (7):

$$\Delta\phi_s = \arcsin\left(\frac{V_{dB} - V_{dA}}{1.8701 \cdot k}\right), \quad (8)$$

and the rotation rate of FOG is

$$\Omega = \frac{\lambda C}{2\pi LD} \cdot \Delta\phi_s,$$

where  $L$  is the length of the sensor fiber coil;  $D$  is the diameter of the fiber coil;  $C$  is the velocity of light in vacuum;  $\lambda$  is the wavelength of light source.

Almost all open-loop FOG uses PZT fiber-optic phase modulator because it is cheap and easy to be fabricated. There are two main parameters, namely modulation coefficient  $K_p$  and the phase delay  $\alpha$ <sup>[4]</sup>, are temperature dependent and will effect performance of FOG. In Eq. (2),  $\omega_m$  and  $\tau$  are set previously and will not change with environment. When operating condition changes, the variation of  $K_p$  will result in  $\phi_m$  change. To stabilize  $\phi_m$ , the modulation amplitude  $V_m$  can be used to compensate the variation of  $K_p$  and keep their product steady. In ordinary case,  $\alpha$  is regarded as a constant value that can be compensated with electric phase shifter. But in practice, it will vary with temperature and may bring big drift to FOG. To get the accurate values of point *A* and *B*, the A/D sampling trigger pulse must correspond to point *A* and *B* exactly. Because the second harmonic component (waveform  $V_2$  in Fig. 2) has constant phase relation with the fundamental component and the sampling frequency is twice the modulation frequency, it can be used to generate the sampling pulse needed. In this

scheme, it is picked from output wave first and then be processed with phase shift and shaping circuit, at last the pulse which corresponding to the key points *A* and *B* are obtained and the corresponding state can be kept whatever the phase delay  $\alpha$  changes. The automatic correlation sampling is realized and the drift due to  $\alpha$  has been eliminated.

When the modulation depth  $\phi_m$  was set to 4.35, the peak-peak value of output waveform  $V_o$  in Fig. 2 will be  $2k$  according to Eq. (3) and related only with the gain (including optical power and electric circuit gain) of FOG. When the gain changes, peak-peak value will changes. So, the changed value can be used as feedback to adjust the gain of electric circuit or source power, the whole gain can be controlled and keep steady.

Figure 3 is the diagram of signal detection scheme demonstrated above. The optical section is same as that shown in Fig. 1. In this FOG, the wavelength of superluminescent diode source (SLD) is  $1.3 \mu\text{m}$  and two polarization maintain (PM) fiber couplers are used. The polarized is fabricated with single polarization optical fiber and the sensor coil is PM fiber about 60-mm diameter and 200-m length. The modulator is PZT modulator which modulation frequency is about 35 kHz and PIN-FET detector is used too.

In Fig. 3, isolate capacitor is used to isolate DC from the output. The whole gain is controlled by adjusting the light power of SLD according to detected peak-peak value. A/D converter (16 bits, 100 kHz) is used to digitize points *A* and *B* in waveform  $V_o$ . The trigger pulse generator includes a band-pass filter, which has the central frequency of twice of the fundamental frequency and takes the role to pick up second harmonic component from output, and a simple phase shift and a comparing and shaping circuit. DSP TMS320C30 takes the charge

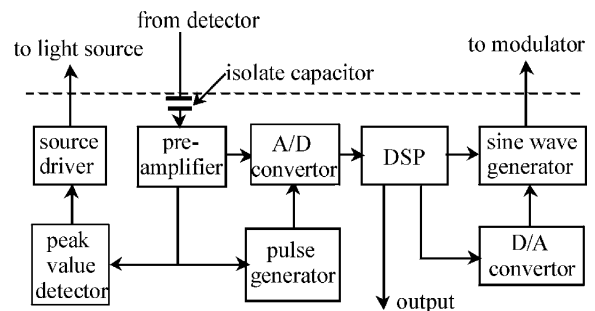


Fig. 3. The diagram of signal detection scheme.

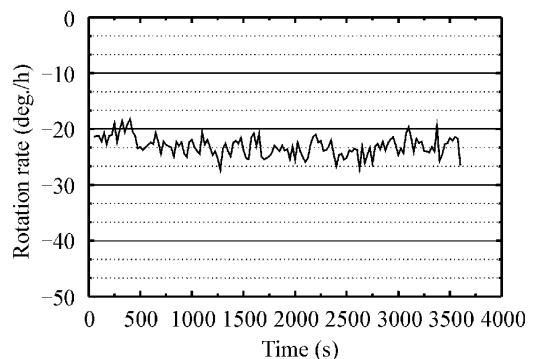


Fig. 4. Zero-bias test result.

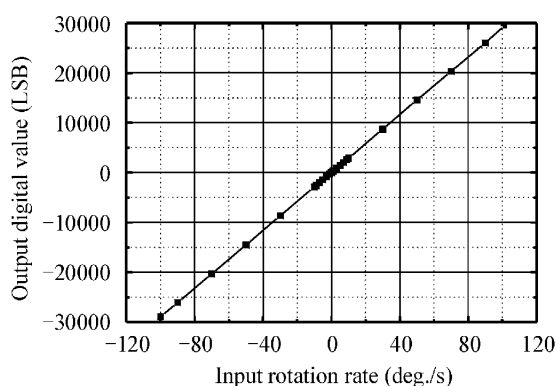


Fig. 5. Test result of scale factor.

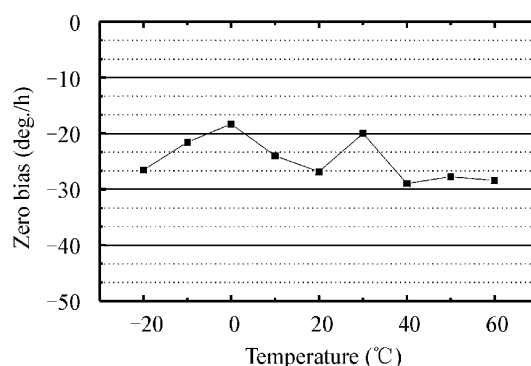


Fig. 6. Zero bias versus temperature.

of calculating and control and input/output. The amplitude of modulation signal is determined by D/A converter (12 bits) output level while the modulation frequency is given by DSP directly. The digital output is standard RS232 port.

An experimental system was made according to Fig. 3. In room condition, the zero bias and scale factor non-linearity are tested. The results are shown in Figs. 4 and 5 and the values are  $1.8^\circ/\text{h}$  and 2325 ppm within  $\pm 100^\circ/\text{s}$  dynamic range respectively. Under the  $-20 - +60^\circ\text{C}$  temperature range, the zero bias drift is tested too. The result is shown in Fig. 6 and the drift is  $3.9^\circ/\text{h}$ .

In the open-loop FOG demonstrated, digital technology was taken, the bias drift due to analog circuit is eliminated. With gain control, the gain error which can result in non-linearity and zero bias is reduced greatly too. Otherwise, the sampling rate is only twice of the

modulation frequency, expensive high speed A/D converter is not necessary. Further more, the scheme is all digital, not only the control and calculation can be processed with DSP, but also the extra error and non-linearity can be compensated with it. The three main error sources (drift due to variation of  $K_p$ ,  $\alpha$  and  $k$ ) which limit the performance have been reduced, that make the open-loop FOG practical.

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