Parameter optimization analysis to minimise the backscattering error in localized thermal tuneable fiber ring resonator gyroscope

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Abstract: The accuracy of the resonant frequency servo loop is a major concern for the high-performance operation of a resonant fiber optic gyro. For instance, a bias value as large as tens or even hundreds of degrees/hour has been observed at the demodulated output of a resonant frequency servo loop. The traditional frequency servo mechanism is not an efficient tool to address this problem. In our previous transitions, we proposed a novel method to minimize the bias value to the level of shot noise by refractive index modulation by thermally tuneable resonator. In this paper, we have done some optimization analysis on parameter values of phase modulator to minimize the Backscattering error to enhance the sensitivity of the gyro. With optimized parameters value we achieved the bias value of R-FOG to 1.992^0/hr.

Key words: Resonator fiber optic Gyroscope, Fiber resonator, Backscattering noise, Thermal tuning, Bias, Frequency stabilization.

I. INTRODUCTION

Resonator Fiber Optic Gyro(R-FOG), detecting rotation signal based on the resonant frequency difference between the clockwise (CW) and the counter-clockwise (CCW) propagating light waves in a fiber ring resonator according to the sagnac effect, it is expected to satisfy the Inertial navigation system (INS) requirement (10^{-7} rad/s) with a fiber as short as 5 to 10 meters [1]. In practice, however, its performance achieved to date is still below expectation due to noises from various effects. Among which the noise induced by the backscattering and the polarization fluctuation are the most important [2]. These two types of noise limit the gyro sensitivity far greater than the shot noise associated with the photo detectors. The polarization fluctuation induced noise is dominantly caused by the existence of dual Eigen states of polarization (ESOP) in the optical fiber ring resonator (OFRR) and by the birefringence fluctuations of the fiber [3]. The backscattering-induced noise is caused by the non-uniformity of the fiber which constitutes the OFRR. It can be reduced below the shot noise level by the optimization of modulation parameters. The backscattering induced noise is a huge barrier to improving the sensitivity of R-FOG. Carrier wave suppression is usually adopted in the phase modulation technique to reduce the backscattering induced noise [4]. In addition, the phase noise of the laser source and the resonator frequency drift due to the environment fluctuation are also a huge challenge in detection. A proportional integral (PI) controller is adopted in the frequency servo loop to track the resonator frequency of the ring resonator and eliminate the residual error at the lock-in frequency. Xu-lin Zhang et.al [5] proposed a detection system by the PM spectroscopy technique using $LiNbO_3$ phase modulators. They derived the comprehensive expression of the demodulated signal using the Bessel function expansion and the optical field overlapping method.

Here in this paper, we analyse the thermally tuneable resonator fiber optic gyroscope based on the PM spectroscopy technique. The optimized modulation frequency and modulation index were found to make the slope of the demodulated curve maximal.

II. GYRO CONFIGURATION AND THEORY

Figure.1. shows the experimental setup of the proposed thermally tuneable RFOG with the FBGA based resonant frequency servo loop. The polarization maintaining fiber

(PMF), transmission type OFRR with twin 90^0 polarization axis rotated splices is the key rotation sensing element in RFOG. The output light from a semiconductor is divided into two equivalent beams by the coupler C1. Both $LiNbO_3$ phase modulators PM1 and PM2 are driven by $V_1\sin(2\pi f_1 t)$ and $V_2\sin(2\pi f_2 t)$, respectively. The output of the photo detector PD1 is fed back through the lock-in amplifier LIA1 to the PI controller to reduce the reciprocal noise, such as the laser frequency noise. The demodulated signal of the counter -clockwise (CCW) light wave from the lock-in amplifier LIA2 is used as the open-loop readout of the rotation rate.

The frequency stabilization loop was composed of a thermally tuneable resonator, a frequency discriminator, and a PI controller, as shown in figure.2. The frequency discriminator, which is based on the phase modulation spectrum technology [5] and the fiber ring resonator (FRR), converts the optical frequency fluctuations of the laser into the voltage fluctuations by the discriminative slope D. A thermally tuneable resonator includes a resonator coil having a resonance wavelength which changes as a function of temperature. The resonant wavelength is given by eqn.1.

$$m\lambda = nL \tag{1}$$

Where L is a resonator length, n is the refractive index of the material, and m is an integer. A resonator's resonance wavelength is related to the resonator material and its index of refraction, so changing the resonator refractive index by thermal tuning leads to a corresponding change in the resonator resonance wavelength. For thermal tuning, the resonance wavelength shift with temperature can be expressed as [6]:

$$\Delta\lambda = \lambda \frac{\Delta n \Delta R}{nR} \tag{2}$$

Here λ is the wavelength of the optical signal. Δn is the change in the resonator material's index of refraction, ΔR change in resonator's Radius with temperature, n is the effective index of refraction of the resonator material, and R is the Radius of the fiber ring resonator. Therefore, resonant frequency deviation with the temperature in the resonator is given by Eqn.3.

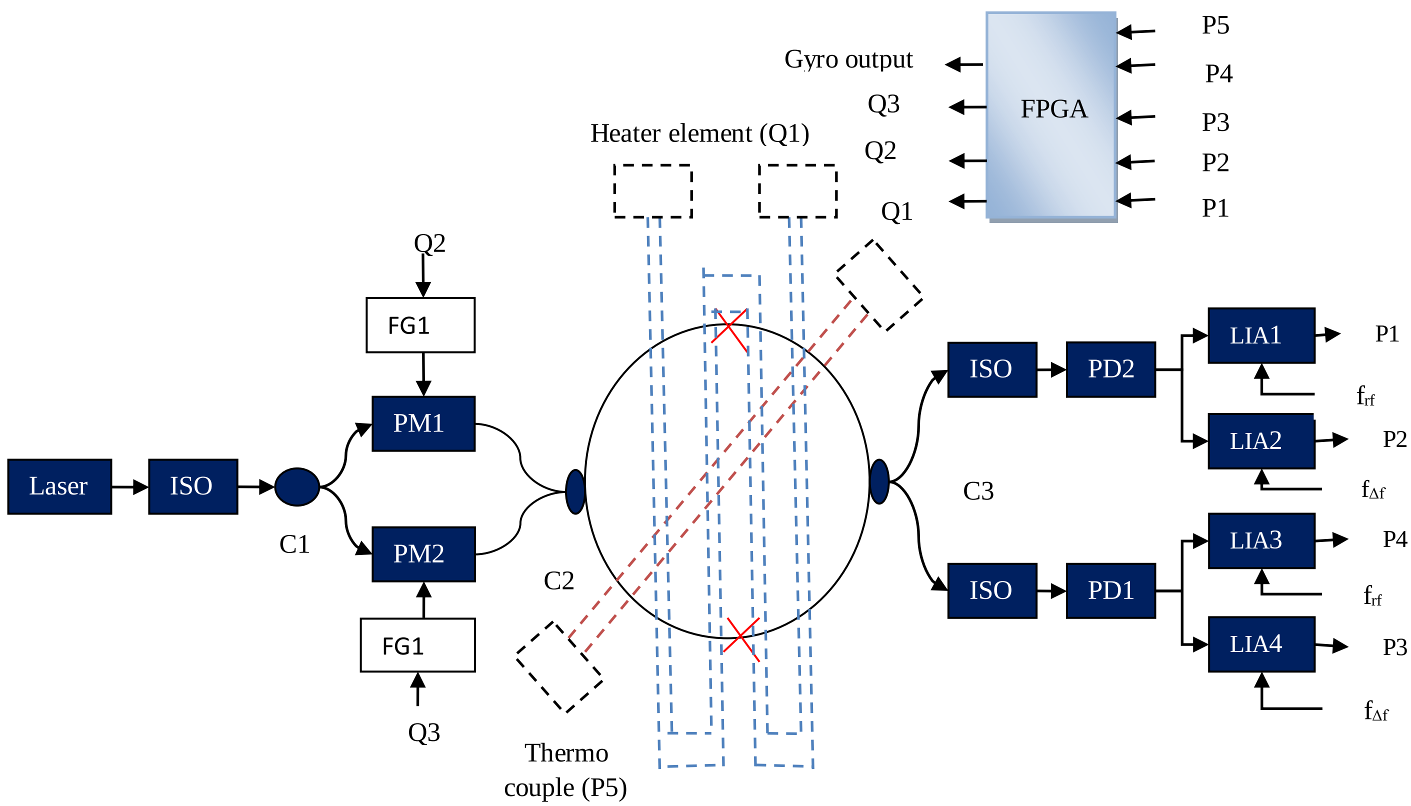

Fig.1. Proposed resonator fiber optic gyro (RFOG) configuration

Signal processing module:

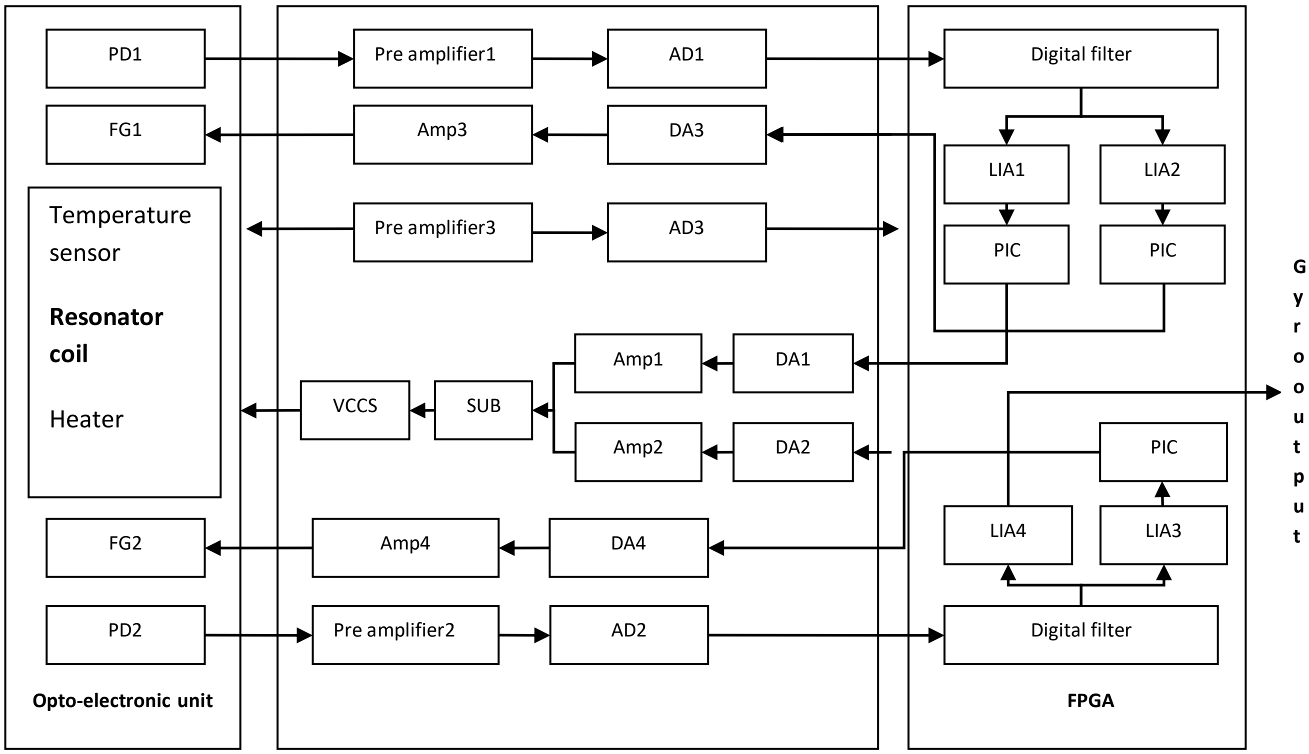

Fig.2. single FPGA based signal processing module.

$$\frac{d\upsilon}{dT} = \frac{-c}{\lambda^2}[\lambda \frac{\frac{\Delta n}{dT} \frac{\Delta R}{dT}}{nR}] \qquad (3)$$

For thermal tuning, we placed a thin-film surface resistance heater with the resonator for effecting localized heating of an optical resonator [7]. The thin film surface resistance heater was formed by placing a resistive element between two terminating electrical pads. The heater was energized with the servo control loop by using the PI controller thus the current flows through the resistive element. The compensated frequency by the heating power P_A can be expressed as,

$$\Delta f = \frac{-c}{\lambda}[\frac{\frac{\Delta n}{dT} \frac{\Delta R}{dT}}{nR}]\Delta T(P_A) \qquad (4)$$

where

$$\Delta(P_A) = (P_A t_w)/[((S_H K_W)*(1+0.88t_w))/w]$$

P_A is the heating power, S_H is the area of the heater, w_h is the width of the heater, t_w is the wave guide thickness and K_W is the thermal conductivity of the cladding. The total width $w=2w_h$.

In order to accurately control the shift in resonance wavelength using heater shown in Figure.2. We used extremely well characterized and stable electric heater (cts-pet-005) for which temperature can be closely correlated to input power. Alternatively, the resonator temperature locally monitored by RTD arrangement. The resonator that was temperature closely regulated by using the feedback loop to control energization of the heater resistive element.

III. THEORETICAL ANALYSIS

Here we analyze the detection system based on the PM spectroscopy technique [5], and the optimal modulation frequency and modulation index are obtained. According to the theoretical analysis, an open loop operation experimental system is set-up. The open loop gyro output signal is observed successively.

Figure.1. shows the experimental setup of the R-FOG by using the PM spectroscopy technique. The coupling ratios for couplers C1, C2, and C3 are all designed as 50:50, 27:73, and 1:99 respectively. The output light from the fiber laser (FL) is split into two beams by C1. Each beam is sine wave phase modulated by the LiNbO3 phase modulators PM1 and PM2 before being injected into the resonator.

The clock wise (CW) and counter-clockwise (CCW) light waves in the resonator are sensed in the transition mode by photodiodes PD1 and PD2, respectively. Subsequently, the signals from PD1 and PD2 are demodulated by lock-in amplifiers LIA1 and LIA2. In the CCW direction, the CCW resonant frequency (f_{CCW}) of resonator coil is locked to the frequency of the FL (f_{FL}) by the feedback circuit (FBC). In the open loop operation, the output signal from LIA2 will give out the gyro output.

In the CW operation, using the Bessel function expansion, the input electric field of the resonator is derived as

$$E_{R-in}(t) = \frac{\sqrt{(1-\alpha_{c1})(1-\alpha_{c2})}}{2} E_0 * \sum_{n=-\alpha}^{\alpha} J_n(M) * \exp i2\pi(f_{FL} + nf_2)t, \quad (5)$$

Where, E_0 is the amplitude of the electric field output from the FL. And α_{c1},α_{c2} are the excess losses of C1 and C2, respectively. $M=V_2\pi/V_\pi$ is the modulation index. Here V_π is the half wave voltage for the PM2. V_2 and f_2 are the amplitude and frequency of the modulation signal applied to the PM2, respectively and n is the integer.

By the overlapping field method [8], the electric field out from the resonator is expressed as

$$E_{R-out}(t) = \frac{\sqrt{(1-\alpha_{c1})(1-\alpha_{c2})}}{2} E_0 \sum_{n=-\alpha}^{\alpha} J_n(M) * e^{i2\pi f_n t} h_n e^{i\phi_n}, \quad (6)$$

Where

$$h_n = (1-\alpha_c)\sqrt{1-\rho\frac{(1-Q)^2}{(1-Q)^2 + 4Q\sin^2(\pi\frac{\Delta f + nf_2}{FSR})}} \quad (6a)$$

$$\rho = 1 - \frac{1}{(1-\alpha_c)}[\frac{T-(TQ+R)}{1-Q}]^2, \quad (6b)$$

$$\phi_n = \arctan[\frac{R\sin(2\pi\frac{\Delta f + nf_2}{FSR})}{T+(TQ+R)Q-(2TQ+R)\cos(2\pi\frac{\Delta f + nf_2}{FSR})}] \quad (6c)$$

$$T = \sqrt{1-k_c}\sqrt{1-\alpha_c} \quad (6d)$$

$$R = k_c(1-\alpha_c)\sqrt{1-\alpha_L} \quad (6e)$$

$$Q = \sqrt{1-\alpha_L}\sqrt{1-k_c}\sqrt{1-\alpha_c} \quad (6f)$$

h_n and ϕ_n represent the amplitude and the phase of the transmission function for the resonator, respectively. ρ is the resonance depth of the resonator. The free spectral range (FSR) is defined as c_0/n_0L; n_0 is the refractive index of the fiber; c_0 is the light velocity in vacuum; $f_n=f_{FL}+nf_2$ and n is a integer. And f_{CW} is the resonant frequency for the CW light wave. α_L is the total loss of the fiber. k_C And α_C are the coupling ratio and the excess loss of coupler C, respectively.

Then, the output signal from PD2 is expressed as

$$V_{PD-out} = \frac{1}{2}A\sum_{n=-\alpha}^{\alpha}\sum_{n'=-\alpha}^{\alpha} J_n(M)J_{n'}(M) * e^{i[2\pi(n-n')f_2t]}h_n h_{n'} e^{i(\phi_n-\phi_{n'})}, \quad (7)$$

Where

$$A = \frac{1}{4}(1-\alpha_{c3})(1-\alpha_{c2})(1-\alpha_{c1})NE_0^2 \quad (8)$$

α_{C3} represents the excess loss of coupler C3, and N is the responsivity of PD2.

Demodulating the first harmonic by the in-phase measurement and using a band pass filter, only the component with sin $2\pi f_2$ exists after LIA2;

$$V_{out} = AG\sum_n J_n(M)J_{n+1}(M)\{h_n h_{n+1}\sin(\phi_{n+1}-\phi_n) - h_{-n}h_{-(n+1)}\sin[\phi_{-n}-\phi_{-(n-1)}]\} \quad (9)$$

Where G is the total gain lock-in amplifier LIA2;

Both h(.) and ϕ(.) are the functions of Δf. So Eqn (9) gives the relationship between the demodulated signal V_{out} And the resonant frequency deviation Δf. The expression of the demodulated signal for the CCW light wave is similar to that for the CW light wave.

In the R-FOG, the resonant frequency tracing process is based on the slope of the centre part of the demodulated curve output from the LIA. Maximizing the slope will improve the detection sensitivity of the gyro. According to Eqn (9), the demodulated signal slope at resonant point f_{CW} can be written as

$$K = \left| \frac{dV_{out}}{d\Delta f} \right|_{\Delta f = 0}$$

$$= \left| \begin{array}{l} AG\sum_{n} J_n J_{n+1} \{[h'_n h_{n+1} \sin(\phi_{n+1} - \phi_n) + h_n h'_{n+1} \\ \quad * \sin(\phi_{n+1} - \phi_n) + h_n h_{n+1}(\phi'_{n+1} - \phi'_n) * \cos(\phi_{n+1} - \phi_n) \\ -[h'_{-n} h_{-(n+1)} \sin(\phi_{-n} - \phi_{-n-1}) + h_{-n} h'_{-(n+1)} \sin(\phi_{-n} - \phi_{-n-1}) \\ + h_{-n} h_{-(n+1)}(\phi'_{-n-1} - \phi'_{-n}) * \cos(\phi_{-n} - \phi_{-n-1})]\} \end{array} \right|_{\Delta f = 0} \quad (10)$$

Where h' and ϕ' are the differentials of h and ϕ respectively.

In order to analyse and to improve the sensitivity of the gyro, we have done some simulations on modulation frequency, modulation index and fiber resonator coil length on the slope of the demodulated signal. Then we try to minimize the backscattering noise, on the measurement of rotation rate, by optimizing parameters.

As we observed from the Figure.3, the slope of the demodulation signal at resonant point f_{cw} is maximum at modulation frequency 1.3 M htz

As we observed from the Figure.4, slope of the demodulation signal at resonant point f_{cw} is increasing with decreasing resonator fiber coil length and also at modulation frequency 1M htz slope of the demodulation output is more.

As we observed from the Figure.5, slope of the demodulation signal at resonant point f_{cw} is maximum at modulation index M is equal to one with modulation frequency 1M htz.

From the above parameter analysis with the optimized values such as modulation frequency f2 is 1.2 M htz, modulation index M is equal to one, and with fiber resonator coil length 5m. Finally, from Figure.6, we found the demodulation output signal at LIA2, V_{out} with respect to the resonance frequency deviation with the maximum slope.

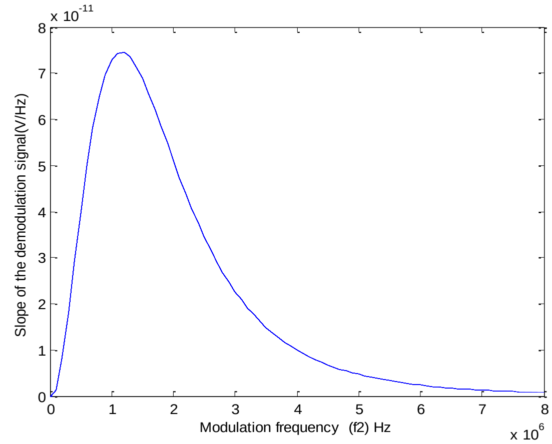

Figure.3. Slope of the demodulation signal at resonant point f_{cw} with the modulation frequencies f2.

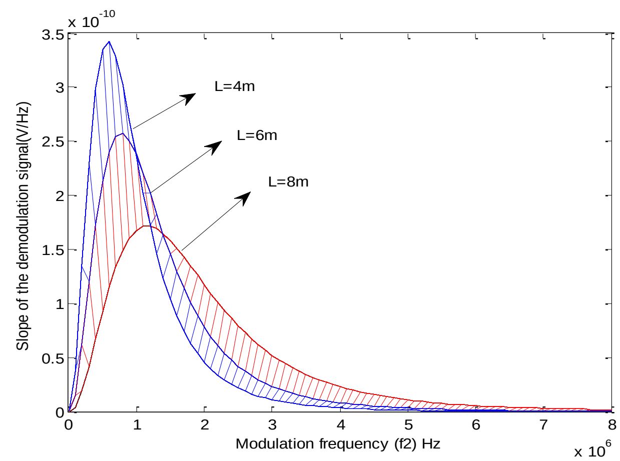

Figure.4. Slope of the demodulation signal at resonant point f_{cw} with the modulation frequencies f2 of different length of the fiber.

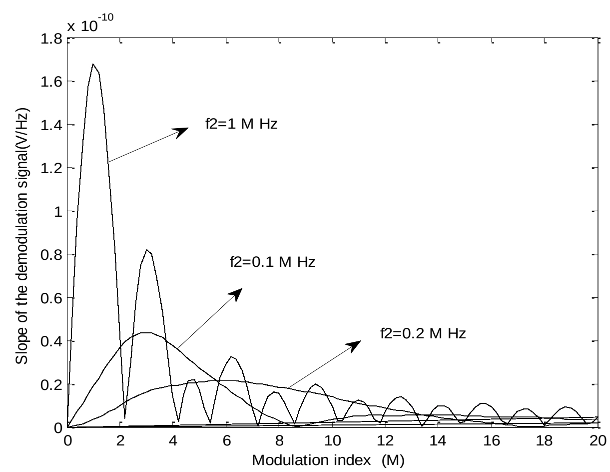

Figure.5. Slope of the demodulation signal at resonant point f_{cw} versus modulation Index M with modulation frequencies f2 of 0.2,0.1 and 1M htz.

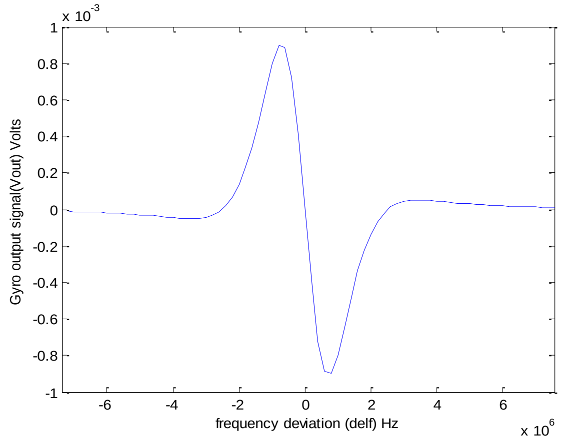

Figure.6. Demodulated signal with the modulation frequencies 1.2 M htz. And modulation index M of 1.0.

IV. Results and Discussion

Figure.1. shows the experimental setup of the R-FOG, the fiber resonator is composed of a 5 m long polarization-maintaining fiber. The diameter of the resonator is approximately 0.11 m and the wavelength of the FL is 1550 nm. The excess losses of C1 and C2 and C3 are all 0.5dB. The total loss of the fiber is 0.05dB. The responsivities of PD1 and PD2 are both 0.95V/mW. The output intensity of the FL is 10 mW. The integration time of the system is 1 s. Therefore, the shot noise-limited sensitivity is estimated to be 1.61deg/hr. first the resonance curve of the resonator is swept. When a low-frequency sawtooth-wave voltage is applied to the Heater coil, the resonant frequency of resonator coil will change linearly with time. As can be seen these simulation results based on the theoretical values. Figure.6, gives the demodulated curve with the modulation frequency f2 of 1MHz. from figure.6, one can see that the demodulated curve has good linearity and a steep slope near the resonant point. This means that resonant point detection with high accuracy is possible.

Figure.2. shows the signal detection and processing scheme. In which signal processing is implemented on a single field programmable gate array (FPGA). The demodulated output of LIA1 is regarded as the deviation between the frequency of laser source and the resonance frequency of ring resonator. so it is used to tune the two frequencies to equal values through FBC. The FBC is composed of proportional integrator control (PIC), an D to A convertor in compensation with temperature sensor value; and the resultant subtracted voltage is used to power up the heater. The demodulated output at LIA2 is as shown in figure.7; at steady state is the gyro output rotation rate signal, which is the bias of the gyro due to noise sources. Both the LIAs are composed of the preamplifier, A to D convertor and the low-pass filter.

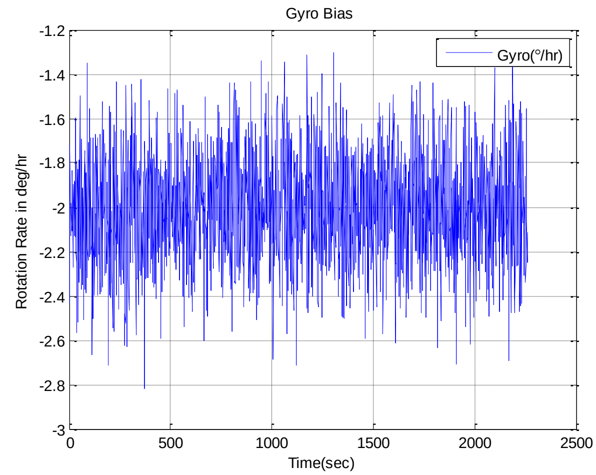

Figure.7. Gyro output signal at LIA2 as function of time.

V. Conclusion

A resonant frequency of the resonator is locked to laser frequency, precisely by refractive index modulation by thermally tuneable resonator. Once locked, the effect of backscattering noise has minimized by the optimization of modulation frequency and modulation index of Phase modulator, using single Field Programmable Gate Array (FPGA). The Backscattering noise with the reciprocal fluctuations in laser frequency is suppressed and achieved bias value to the level of 1.992^0/hr. Further to increase the sensitivity of the device and to decrease the bias to the level of shot noise we need to work on Kerr effect, thermal fluctuations in source and laser intensity error.

VI. Disclosers

There are no financial conflicts of interest to disclose.

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