Effect of input intensity fluctuation of fiber ring resonator on resonator fiber optic gyroscope

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Abstract: Resonator fiber optic gyro (RFOG) is a high accuracy inertial rotation sensor based on Sagnac effect. As one of reciprocity noises in RFOG, input intensity fluctuation of fiber ring resonator (FRR) would lead to detection error. Firstly, the mechanism of noise induced by FRR input intensity fluctuation was investigated. Transmission characters of FRR and demodulation output with different input intensities were researched theoretically and experimentally. The expression of detection error caused by input intensity fluctuation was derived. When rotation rate was 500 (°)/s and input intensity was 0.69 mW, a variation of 0.0075 mW would cause an error as large as 5.26 (°)/s. Secondly, the effect of input intensity fluctuation on scale factor was studied. It was found that the linear region of demodulation curve would be distorted as input intensity fluctuation increase and scale factor nonlinearity of gyro output would deteriorate too. This work proved a reference for estimating input intensity fluctuation noise in a RFOG system.

Key words: resonator;　fiber gyroscope;　noise;　sensitivity

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光纤环形谐振腔输入功率波动对谐振式光纤陀螺的影响

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摘　要: 谐振式光纤陀螺是一种基于 Sagnac 效应的高精度惯性传感器。作为一种互异性噪声,光纤谐振腔输入功率的波动会造成陀螺的检测误差。首先,分析了光纤谐振腔输入功率波动产生噪声的机理。通过对不同输入功率下的谐振腔传输特性和陀螺解调输出的理论及实验分析得到了谐振腔输入功率波动引起的检测误差的表达式。当输入角速度为 500 (°)/s、输入功率为 0.69 mW 时,0.007 5 mW 的功率波动会引起 5.26 (°)/s 的检测误差。其次,研究了谐振腔输入功率波动对陀螺标度因数的影响。通过计算发现随着输入功率波动的增大,解调曲线的线性区将会发生扭曲,同时陀螺的标度因数非线性度会恶化,为谐振式光纤陀螺中输入功率波动噪声的估测提供了参考。

关键词: 谐振腔;　光纤陀螺;　噪声;　灵敏度

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0 Introduction

Since Vali and Shorthill proposed interferometric fiber optic gyroscope (IFOG) in 1976 IFOG has been widely used in both civil and military[1]. Although IFOG has been mature, it is not suitable for many situation due to its long fiber and large size. Comparing to IFOG, resonator fiber optic gyroscope (RFOG) would achieve a high accuracy with ten meters fiber which has potential to be inertial navigation sensor of next generation[2-3]. Different from IFOG, RFOG needs a narrow linewidth laser to improve its sensitivity. However, when narrow linewidth laser is applied, some optic noises are introduced and extremely limit the performance of RFOG [4-6]. As a reciprocity noise, input intensity fluctuation of fiber ring resonator (FRR) would decrease the performance of RFOG. Effect of laser intensity variation in resonator integrated optic gyro has been researched by Lei M, et al. in 2013 [7]. They found that not only is the laser intensity noise influenced by intensity variation but also it has a high correlation with the nonzero bias between the clockwise and counterclockwise resonant frequency. Ying D, et al. studied residual intensity modulation(RIM) in resonator fiber optic gyro deeply[8]. He concluded that RIM-induced error varies with RIM coefficient and modulation frequency. When the modulation frequency deviates from the optimum value, a 253.4 (°)/h induced error would occur. So the input intensity noise fluctuation cannot be ignored. Both laser intensity variation and RIM effect would generate input intensity fluctuation of FRR. To evaluate the optical intensity noise in RFOG system, it is necessary to focus on input intensity fluctuation of FRR.

In this paper, FRR input intensity fluctuation noise in a RFOG based on sine wave modulation was analyzed by using optic field overlapping method. Transmission characters and demodulation curve of FRR with different input intensities were measured in experiment which were according with the theory. Through numerical calculation, scale factor nonlinearity with intensity fluctuation was studied.

1 Principle

The system configuration of a RFOG is illustrated in Fig.1, which composed of distributed feedback(DFB) fiber laser(linewidth less than 100 Hz), $LiNbO_3$ phase modulators (PM), FRR, photoelectric detectors, lock in amplifiers and control circuit. Light wave signal is launched by DFB fiber laser then divided into two beams by splitter C1. The two PMs which drived by sinusoidal waveform with different frequencies f_1 and f_2 are used to modulate the two beams. Through fiber coupler C2 the modulated signals are coupled into fiber ring resonator. Clockwise (CW) signal is detected and demodulated by PD_2 and LIA_2, respectively. Output of LIA_2 controls the frequency of the DFB fiber laser to lock on the CW resonant frequency as a feedback. Counterclockwise (CCW) signal is detected by PD_1 and demodulated by LIA_1 then export as open-loop signal of RFOG. Taking the CCW signal as an example, the output of DFB laser could be express as:

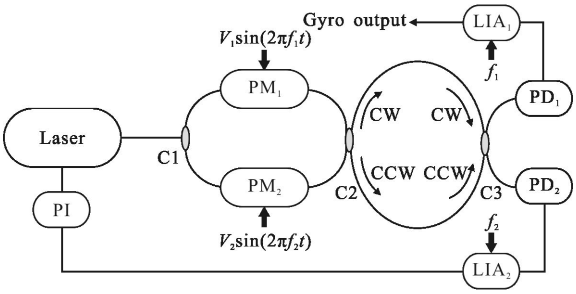

Fig.1 Schematic configuration of RFOG

$$E_{in}=E_0\exp[j(2\pi f_0 t+\varphi_0)] \tag{1}$$

where E_0 is amplitude of the electric field of the laser light; f_0 is frequency of light and φ_0 is initial phase. After the modulation of PM_1, the electric field is written as:

$$E_{PM_1}=KE_0\sum_{n=-\infty}^{\infty}J_n(M)\exp[j(2\pi f_n+\phi_0)] \tag{2}$$

where $K=\sqrt{k_1(1-a_{C1})(1-a_{PM_1})}$, k_1 is the coupling coefficient of C1, a_{C1} and a_{PM_1} are insert loss of C1 and PM₁, respectively; $J_n(M)$ is n order Bessel function, $M=\pi V_1/V_\pi$ is modulation index, V_1 is amplitude of sinusoidal wave, V_π is half-wave voltage of PM₁; $f_n=f_0+nf_{PM_1}$, f_{PM_1} is the frequency of sine wave. After propagating in the FRR, the output signal of FRR could be written as:

$$E_{out}=KE_0\sum_{n=-\infty}^{\infty}J_n(M)\exp[j(2\pi f_n+\phi_0)]A_n\exp(j\phi_n) \tag{3}$$

A_n and ϕ_n are transfer function of amplitude and phase respective. Where

$$A_n=QR\sqrt{\frac{1}{(1-TR^2)^2+4TR^2\sin^2\left[\frac{\pi(\Delta f+nf_{PM_1})}{FSR}\right]}} \tag{4}$$

$$\phi_n=-\frac{\pi f_n}{FSR}-\arctan\left\{\frac{TR^2\sin\left[2\pi(\frac{\Delta f+nf_{PM_1}}{FSR}\right]}{1-TR^2\sin\left[2\pi(\frac{\Delta f+nf_{PM_1}}{FSR}\right]}\right\} \tag{5}$$

where Δf is deviation of laser frequency and resonance frequency; $FSR=c/n_{eff}L$ is free spectral range, c is light velocity in the vacuum, n_{eff} is effective refractive index, L is the length of fiber; $R=\sqrt{1-a_{L/2}}$; $T=\sqrt{(1-k_{C2})(1-k_{C3})(1-a_{C2})(1-a_{C3})}$; $Q=\sqrt{k_{C2}k_{C3}(1-a_{C2})(1-a_{C3})}$, k_2 and k_3 are the coupling coefficient of C2 and C3 respective, a_2 and a_3 are the insert loss of C2 and C3, $a_{L/2}$ is intensity loss for semi-loop of the FRR. According to Eq. (3), the output of PD₁ and LIA₁ could express as:

$$V_{PD_1}=I_0\eta G_1\sum_{n=-\infty}^{\infty}\sum_{n'=-\infty}^{\infty}J_n(M)J_{n'}(M)\times\exp[j(n-n')2\pi f_{PM_1}t]\cdot A_nA_{n'}\exp[j(\phi_n-\phi_{n'})] \tag{6}$$

$$V_{LIA_1}=-I_0G_2\eta\sum_{n=-\infty}^{\infty}J_nJ_{n+1}A_nA_{n+1}\sin(\phi_{n+1}-\phi_n) \tag{7}$$

where $I_0=k_{C1}(1-a_{C1})(1-a_{PM_1})I_{laser}$ is input intensity of FRR; η is the photoelectric conversion factor of PD₁; G_1 and G_2 is the gain of PD₁ and LIA₁.

2 Simulation and experiment

From Eqs.(6) and (7), it can be seen that both output of PD₁ and LIA₁ are functions of input intensity of FRR. However, due to the influence of varying environment, instability of laser and RIM effect, the input intensity of FRR would fluctuate which has an influence on transmission characters of FRR and demodulation output. To show the effect of input intensity fluctuation on gyro output clearly, transmission of FRR and demodulation output with different input intensity is studied. The length of fiber is 4 m, diameter of resonator is 0.12 m, k_1 is 0.5, k_2 is 0.1, k_3 is 0.01 in experiment. The modulation voltage V_1 and modulation frequency are set to 2 V and 500 kHz, respectively.

FRR is the core sensing element of a RFOG whose transmission characters would have strong impact on performance of RFOG. Figure 2 (a) illustrates the transmission characters of FRR with different input intensities. The peak value of resonance curve and full width at half maximum(FWHM) would increase as input intensity increases. When input intensity is 1.12 mW, the peak value of resonance curve is about 0.055 V and FWHM of transmission is 6.9 MHz, while the input intensity is 1.4 mW, peak value of resonance curve and FWHM increase to 0.69 V and 7.2 MHz,

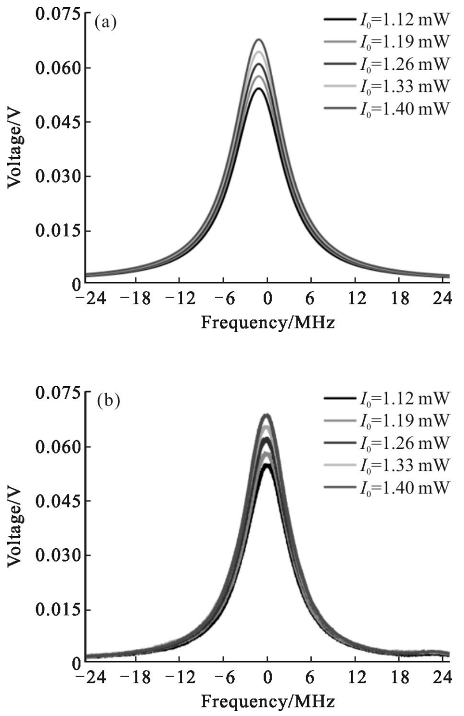

Fig.2 Transmission of FRR with different input intensities

respectively. Figure 2 (b) shows the experimental results, which agree with theoretically analysis well.

Figure 3 (a) and (b) are the simulated and experimental measured demodulation curves with different input intensities. The region near resonant point is the work region of RFOG and the slope of demodulation curve at resonant point is regard as scale factor of RFOG which indicates ratio of the gyro output to the input rotation rate. It can be seen that the slope of demodulation curve is various with different input intensity which means that when the input rotation rate is fixed the demodulation output would fluctuate and generate error. The error would increase with input rotation rate increase.

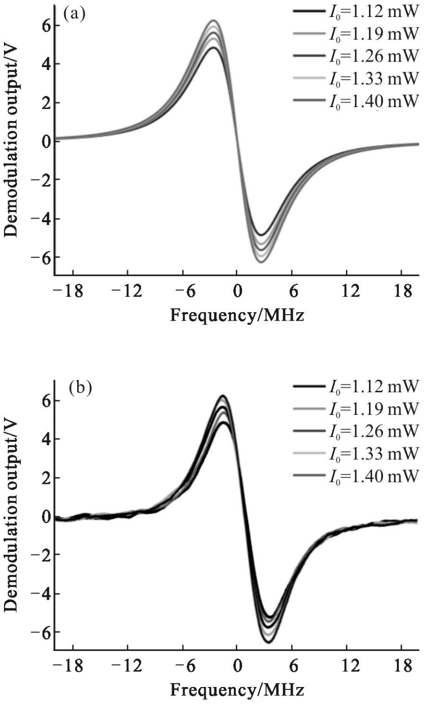

Fig.3 Demodulation output with different input intensities

Figure 4 shows the relationship between input intensity and slope of demodulation curve at resonance point. It can be seen that slope of demodulation curve is proportional to input intensity. Slope of demodulation curve can be derived as:

$$K_S=-2.948\times I_0\ \mathrm{V/MHz} \tag{8}$$

The demodulation output error caused input intensity fluctuation and the detection error of RFOG can be expressed as:

$$\Delta V=\Delta I_0\times K_S\times\frac{D\Omega_{\mathrm{input}}}{n\lambda}\times\frac{\pi}{180}\mathrm{V} \tag{9}$$

$$\Omega_{\mathrm{error}}=\frac{\Delta I_0}{I_0\sqrt{N}}\Omega_{\mathrm{input}}\ (^\circ)/\mathrm{s} \tag{10}$$

where N is defined as the ratio of the RFOG output speed to the sampling ratio of the intensity fluctuation.

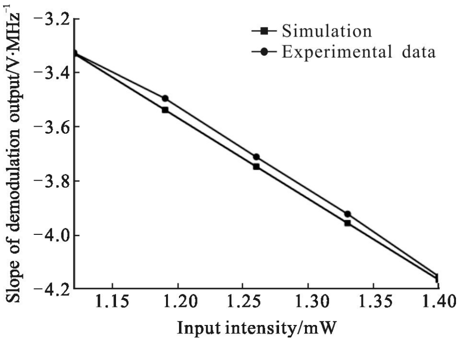

Fig.4 Relationship between slope of demodulation curve and input intensity

Figure 5 shows the input intensity of FRR in 5 s measured by optical power meter (Newport model 2396-R). The average input intensity is about 0.69 mW and the maximum variation is about 0.007 5 mW. In order to confirm the requirements of dynamic range for tactical application, the dynamic range is set to ±500 (°)/s. When the variation is 1%, input angular velocity is 500 (°)/s, the error of demodulation output would be 0.01 V and corresponding angular velocity would be 5.43 (°)/s which can not be neglected in a high accuracy RFOG, meanwhile, this error would increase as the input intensity variation increase.

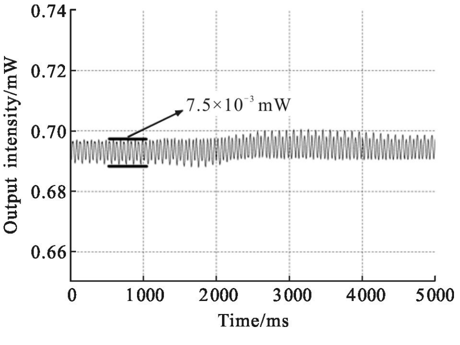

Fig.5 Input intensity of FRR in 5 s

In order to show the intensity fluctuation effect on demodulation output, the maximum variation is set to 0.03 mW. Figure 6 (a) illustrates demodulation output with a fluctuation of 0.03 mW, it can be seen that with the increasing of input angular velocity, the demodulation output is no longer linear and the distortion rate would increase as input angular velocity increase. Scale factor nonlinearity is a significant parameter to evaluate the performance of a RFOG. Figure 6 (b) shows the relationship between intensity variation and scale factor nonlinearity. It can be seen that scale factor nonlinearity would increase as intensity variation increase. The scale factor nonlinearity is 0.2% when intensity variation is 0.02%, while intensity variation increase to 2% scale factor nonlinearity increase to 5.5% rapidly.

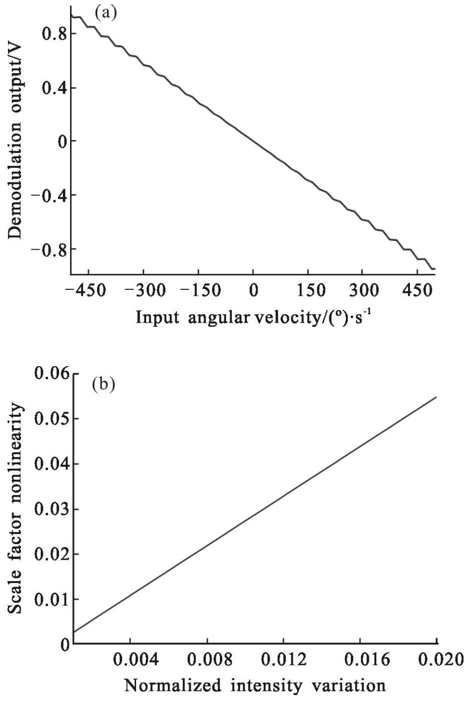

Fig.6 Demodulation output with intensity fluctuation(a) and relationship between intensity variation and scale factor nonlinearity(b)

3 Conclusion

Input intensity fluctuation noise in a RFOG is analyzed in detail. It is concluded that slope of demodulation curve is proportional to the input intensity of FRR. When input intensity fluctuate it would generate detection error in RFOG. This error is also proportional to the input angular velocity. A detection error of 5.26 (°)/s would be caused when input intensity fluctuation is 1% and input angular velocity is 500 (°)/s. Input intensity fluctuation would also exert a passive influence on scale factor of a RFOG. With input intensity variation increasing nonlinearity of scale factor would increase rapidly. To reduce input intensity fluctuation noise, some methods should be used to make the input intensity of FRR stable, such as utilizing feedback control technology and keeping environment steady.

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