Backreflections in resonant micro-optic gyroscope

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Abstract
Backreflection noise is one kind of main optical error in the resonant micro-optic gyroscope (RMOG). Resonance characteristics of backreflection noise in a RMOG is analyzed theoretically. Part of the backreflection noise can not be eliminated by using the traditional phase modulation techniques. This part of backreflection brings a nonzero bias to the output of RMOG due to the asymmetry of resonance curve. Degradation of gyro’s linearity is induced because this part’s transfer curve has two notches with separation proportional to the Sagnac phase shift when the RMOG is rotating. It’s recommended to set the length of straight waveguide to be half the ring length.

1. Introduction

Optical gyro has attracted great attention in navigation fields due to its high accuracy, wide dynamic range as well as immunization of the mechanical abrasion [1–4]. The most common optical gyroscopes include the ring laser gyro (RLG), the interferometer fiber–optical gyro (IFOG) and the micro–optical gyro (MOG). A MOG uses planar waveguides instead of fibers to obtain the Sagnac effect [5]. MOGs are divided into interferometric micro-optic gyroscopes (IMOGs) and resonant micro-optic gyroscopes (RMOGs). Compared with a IMOG, a RMOG will achieve the same performance as an IMOG with two longer magnitudes optical length, hence the RMOG has potential to achieve high accuracy, small size and low cost [6].

However, the performance of a RMOG is limited by several factors, including backscattering noise [7, 8], Kerr effect [9], polarization fluctuation noise [10] and Fresnel backreflection [11]. The backscattering induced error can be effectively reduced by carrier suppression [8]. The Kerr effect noise is relatively small as compared to other optical noises [9]. The polarization fluctuation noise can be reduced by applying temperate box and polarization maintaining waveguide [10]. The Fresnel backreflection discussed in this paper occurs at the coupling end face between the waveguide and fiber. Backreflection noise was briefly analyzed by WANG Jun-jie et al [11]. But the Fabry–Perot cavity formed by the two coupling end faces is ignored in their model. The effects of backreflection on the performance of the RMOG is not clearly analyzed when the gyro is rotating.

In this paper, resonant micro-optic gyroscope model including backreflection noise is established. Taking into account the effect of the Fabry–Perot cavity formed by the two coupling end faces, resonance characteristics of backreflection noise in a RMOG is fully analyzed. The behavior of backreflection noise when the gyro rotates is analyzed theoretically.

2. Model setup

In this paper, the backreflection noise is analyzed in detail in a conceptual RMOG based on a reflective resonator which is shown in figure 1. The lightwave from the laser source was split by the 3 dB coupler C1. The clockwise
(CW) and the counterclockwise (CCW) light from the waveguide-type ring resonator (WRR) were detected by respectively using photodetector PD1 and PD2. The WRR in a planar lightwave circuit (PLC) is usually coupled with fiber in a RMOG [12, 13], which is shown in figure 2. The coupling points will introduce backreflection noise due to the mismatch of refractive index between waveguide and air, which is shown in figure 1 as points A and B. $r_1$ and $r_2$ are reflectivity of point A and B, respectively. $t_1$ and $t_2$ are the coupling ratio of point A and B, respectively.

Considering the backreflection in the WRR, the electric field $E_{12}$ on the detector PD2 can be expressed as the sum of $E_1$, $E_2$, and $E_3$. $E_1$ represents the light which is directly reflected back into the fiber at point A. $E_2$ represents the light which is injected from point A and finally recoupled into fiber at point A. $E_3$ represents the light which is injected from point B and coupled into fiber at point A.

### 3. Backreflection noise for the rest state

#### 3.1. Derivation of the formula

For a reflective resonator, the output light can be divided into two parts. The first part is the light that go through the straight waveguide directly. The second part is the light that coupled into the ring resonator and coupled out to straight waveguide after traveling in the ring resonator. Take the Fabry–Perot cavity into account, the output light can be divided into sections that reflect different times in the Fabry–Perot cavity. Assuming the linewidth of the laser is infinitely small, then $E_1$, $E_2$, and $E_3$ are derived by the overlapping field method [7]

$$E_1 = \sqrt{n} E_0 e^{i(\omega t + \Phi_0)}$$  \hspace{1cm} (1)

$$E_2 = t_1 E_0 e^{i(\omega t + \Phi_3)} \sum_{N=1}^{\infty} \frac{1}{t_1^{(N-1)/2} t_2^{N/2}} e^{i2N\Phi} \left( P + R e^{i\pi} \frac{1}{e^{i\omega t} - Q} \right)^{2N}$$  \hspace{1cm} (2)
where two counterpropagating signals are assumed to have same intensity, \( E_0 \) is the amplitude of light at points A and B, \( f_2 \) is the light source frequency, \( \tau \) is the round trip time of WRR, \( k_2 \) is the wavenumber of light. \( \Phi_0 \) is the phase differential between the incident light at point A and B. \( L \) is the length of waveguide between points A and B, \( k_c \) is coupling ratio of coupler C4, \( \alpha_c \) is the insertion loss of coupler C4, \( \alpha_L \) is total loss of light in the WRR per trip.

Since \( E_1 \) and \( E_2 \) have the same initial phase, the total intensity on PD2 is derived as

\[
I = \frac{1}{2} (I_1 + I_2 + I_3) \frac{1}{2} (|E_1 + E_2|^2 + 2 \text{Re} [E_1 + E_2] E_2^* + |E_3|^2),
\]

where the first term is the backreflection of CW beam, the second term is the interference intensity between the beam of CW and CCW, and the last term is intensity of CCW beam. Each term of equation (7) should be estimated statistically. The first term and the last term are derived as

\[
I_1 = \sqrt{h_2} \sqrt{E_0 e^{i\omega t}} \sum_{N=1}^{\infty} \left( \sqrt{\frac{1}{N\pi}} \right)^{N-1} \left( P e^{i(k_1 + \pi)} + R e^{i(k_2 + \pi)} \right)^{2N-1},
\]

where

\[
P = \sqrt{1 - k_e} \sqrt{1 - \alpha_c},
\]

\[
R = k_e (1 - \alpha_c) \sqrt{1 - \alpha_L},
\]

\[
Q = \sqrt{1 - \alpha_L} \sqrt{1 - k_e} \sqrt{1 - \alpha_c},
\]

Because the phase difference \( \Phi_0 \) between the two counterpropagating beams is not fixed due to the thermal fluctuation \( \zeta \), the second term can be estimated as

\[
I_2 = \sqrt{h_2} h_1 \cos (\phi_R + \zeta),
\]

where \( \phi_R \) is a constant.

### 3.2. Analysis

By modulating the counterpropagating beams in the resonator at different frequencies, the first term \( I_1 \) can be eliminated after demodulation. The interference term \( I_2 \) can be reduced by making it oscillate more frequently, then it can be filtered by a low pass filter. This can be achieved by carrier suppression just like the backscattering noise reduction case [8]. It is also possible to reduce this term by making the two counterpropagating beams non-coherent. So the demodulation signal only contains the information of the last term \( I_3 \).

The behavior of \( I_3 \) at rest is shown in figure 3(a). We note the resonance curve is asymmetric except for the case that the length of waveguide outside the ring is exactly equal to half the ring length (the length of waveguide

![Figure 3](image-url)
outside the ring is closed to the diameter of ring resonator, so the longer case is not taken into account. However, it is very difficult to make this length exactly equal to half the ring length. Figure 3(b) shows a experimental resonance curve of a silicon nitride WRR. The cross section of silicon nitride waveguide is set as 5 μm*60 nm. The lengths of the ring resonator and the straight waveguide are 9.42 cm and 3.9 cm, respectively. The measured finesse of the silicon nitride WRR is 7.95. Due to the Fabry–Perot cavity, the resonance curve shows a non-periodic form which is same as figure 3(a). The blue curve is the fitting result of a straight waveguide with two end faces. The approximate reflectance obtained from fitting is approximately 0.068. Therefore, the resonance notch is slightly asymmetric. So the backreflection noise can cause zero-bias fluctuation due to the antisymmetric resonance curve.

4. Backreflection noise for the rotating state

When the gyro is at rotating, the electric field $E_3$ should be rewritten as

$$E_3 = \sqrt{E_0^2 + E_0^2} e^{i\omega t} \sum_{N=2}^{\infty} \left( \frac{1}{\sqrt{2^N}} \right)^{N-1} (A^{N-1}B^N + B),$$

(11)

$$A = Pe^{i\Delta kL} + Re^{i(kL+\pi)} e^{i(\omega t-\theta)} - Q,$$

(12)

$$B = Pe^{i\Delta kL} + Re^{i(kL+\pi)} e^{i(\omega t+\theta)} - Q.$$  

(13)

In equation (11), $\theta$ is the Sagnac phase shift caused in both directions in the WRR. Numerical evaluations are shown in figures 4(a) and (b) while the length between the points of A and B is set to be half the ring length. It can be seen that the resonance notch is separated as one deep notch and one shallow notch. The frequency difference between these two notches is proportional to the phase shift $\theta$. This characteristic of $I_3$ with two notches will degrade the linearity of gyro’s output, which is related to the frequency difference between the two notches. Also it should be noticed that the asymmetric degree of the main notch will change with Sagnac phase shift slightly due to the interaction between the resonance curves of ring resonator and Fabry–Perot cavity.

To illustrate this effect more specifically, asymmetric degree $k_{\Delta N} = (W_0 - W_1) / (W_0 + W_1)$ is introduced to characterize the degree of asymmetry [14], which is shown in figure 5(a). After calculating the resonance curve by the equation (11), the asymmetry degree was obtained according to the curve. Different relative positions of the resonant notch of the resonant ring are investigated, which is shown is figure 5(b). The first region represents the rising arm of the resonant peak of the Fabry–Perot cavity and the second region represents the descending arm. The middle point is exactly at the resonant peak of the Fabry–Perot.

Figure 5(c) shows the effects of Sagnac phase shift on asymmetry of resonance curve. When the resonant notch of the resonant ring is exactly at middle point, there’s no bias error due to the symmetry of the notch. But the asymmetric degree changes due to the increasing of Sagnac phase shift. When the resonant notch of the resonant ring is at the first region or the second region, the resonance curve is asymmetric, and the asymmetric degree is larger than the notch at middle point. The inflection point of the three curves in figure 5(c) is caused by the interaction of the two resonance notches, which is shown in figures 4(a) and (b). 

Figure 4 (a) Resonance curve in the case of $\theta = 0.2$; (b) resonance curve in the case of $\theta = 0.4$. 

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the case of the first region, we found that the asymmetric degree is approximately 0.03% for 50 dB Fresnel end reflections. According to the [15], a slight asymmetric degree of 0.01% will cause an output bias error of 14.5 °/s in a RMOG with a high finesse WRR. Therefore, the Fresnel reflection must be considered in the future work even when the angle-polish technique is applied to WRR. In order to reduce the asymmetric degree of resonance curve, the length of straight waveguide is recommended to half the ring length.

5. Conclusion

In conclusion, backreflection noise in the RMOG based on a reflective resonator is theoretically analyzed. The transfer curve formula of resonant ring resonator is derived with backreflection noise. The total output intensity is divided into three parts. The first two terms can be eliminated by phase modulation technology, the third term is analyzed theoretically when the RMOG is at rest and rotating. The asymmetric degree will change with the Sagnac phase shift. It’s recommended to set the length of straight waveguide to be half the ring length.

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