# Systematically analysis of resonant fiber optic gyroscope 

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#### Abstract

The research on gyroscopes has lasted for a long time, but there is not a thorough analysis of them. In this paper, a detailed theoretical analysis of fiber ring gyroscope and its gyroscope effect are presented, the performance characteristics of optical resonator gyroscope ranging from transmission function Tfrr, Finesse, $Q$-factor, the gyro sensitivity, signal noise ratio, random walk to dynamic range are all deduced in detail. In addition, a large number of experiments have been done to verify the deduced theoretical results. The sensitivity of the fiber optic gyroscope is analyzed by simulating the relationship between $d Q$ and turn number of fiber ring, make the conclusion that with the increase of turn number of ring, the resonance depth increased while the dQ value decreased, obtain a high sensitivity of $0.21^{\circ} / \mathrm{h}$, random walk of $0.0035^{\circ} / \sqrt{ } \mathrm{h}$, and Q factor of $8 \times 10^{6}$. Moreover, in the digital frequency locked dual rotation gyro experiments, obvious step effect is observed. And the experimental line of frequency difference is very agreement with the theoretical line. The research provides a good theoretical and experimental basis for the study of gyroscopes.


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## 1. Introduction

The fiber ring resonator (FRR) is the core sensing element in a gyroscope system, the study of optical gyroscopes was a hot field in recent years, and they have been widely used in industry and military, they were applied ranging from inertial navigation systems in aircrafts and vessels to control, stabilization and positioning systems for robotics and virtual reality applications [1]. The laser gyroscopes produce two counter propagating beams, and their frequency difference is used to measure the rotation speed, the sensitivity is used to measure the performance of optical gyroscope. There has been many elements influence the sensitivity, such as the quality factors, the diameter of ring resonator, the length of fiber, Finesse, resonance depth, the slope of the resonance curve and so all. A lot of scholars are in study of the influence factors on the sensitivity, like Zhejiang University, Beijing University of Aeronautics and Astronautics, Changchun University of Technology and Kanazawa University. But they all do not have a summary of the elements, so this paper provides an in-depth description.

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## 2. Theory

As shown in Fig. 1, a schematic diagram of resonated fiber optic gyroscope is given as follows:

Light from laser S is translated into isolation 1, and divided to two beams (CW and CCW) by a 3 dB coupler C1. Then the two beams transmit into isolation 2, phase modulator 1 and isolation 3, phase modulator 2, respectively, one of the beams through circulator C2 is coupled into fiber ring resonator, and forming CCW wave, another beam through circulator C3 is coupled into fiber ring resonator, and forming CW wave. The resonance frequency of CW light is detected by detector PD1 through coupler C2, and the resonance frequency of CCW light is3 detected by detector PD2 through coupler C3. In order to detect frequency difference, the CCW light is locked to laser through Lock-in amplifier LIA1, PI circuit and high voltage amplifier. While the CW light through Lock-in amplifier LIA2 is detected as gyro signal $\Delta f$.

Defined $R$ is the radius of the fiber ring resonator, $d$ is the perimeter of the fiber ring. $L$ is the length of the fiber
$L=N \cdot 2 \pi R=N \pi d$,
$A$ is the closed area surrounded by optical path,
$A=N \cdot \pi R^{2}$,
$N$ is the number of the rings.


Fig. 1. (a) Simplified diagram of resonator fiber optic gyroscope and (b) fiber ring resonator FRR structure.

When two counter propagation light beams transmitting into the fiber ring resonator, they will produce frequency difference, this phenomenon also called Sagnac effect.

The frequency difference can be descried as [2]:
$\Delta f=\frac{4 A}{\lambda L} \Omega$
The detailed theoretical analysis of Sagnac effect is:
$t_{C W}=\frac{N \cdot 2 \pi R}{c-R \Omega}$
$t_{\text {CCW }}=\frac{N \cdot 2 \pi R}{c+R \Omega}$
$\Delta t=t_{C W}-t_{C C W}=\frac{2 \pi R \cdot 2 R \Omega}{c^{2}-(R \Omega)^{2}}=\frac{4 A \Omega}{c^{2}-(R \Omega)^{2}}$
Here $t_{C W}$ is the transmission time of clockwise, $t_{C C W}$ is transmission time of counter clockwise.

Considering $c^{2} \gg(\Omega R)^{2}$, so
$\Delta t=\frac{4 A \Omega}{c^{2}}$
Therefore the optical path difference $\Delta L$ is:
$\Delta L=\Delta t \cdot c=\frac{4 A \Omega}{c}$
According to
$\Delta f=\frac{f \cdot \Delta L}{L}=\frac{4 A f \Omega}{c L}$
And in medium of refractive index $n_{e f f}$ :
$v=\frac{c}{n_{\text {eff }}}$
$c=f \cdot \lambda$
So
$\Delta f=\frac{4 A}{\lambda L} \Omega$
Here $\lambda$ is the wavelength of light, $c$ is the velocity of light in vacuum, $V$ is velocity of light propagating in medium $n_{e f f}$.

Next we will deduce the transmission function of optical fiber ring resonator in detail: Considering the temporal coherence of the laser, the output intensity of the FRR normalized by the input intensity can be described as [3,4]:
$T_{F R R}=\frac{I_{\text {out }}}{I_{\text {in }}}=T^{2}-\frac{2 T P \cos \left(2 \pi \tau_{0} f\right)-M}{1+H^{2}-2 H \cos \left(2 \pi \tau_{0} f\right)}$
where
$\left\{\begin{array}{l}M=2 T P H+\frac{P^{\prime 2}}{1-H^{\prime 2}} \cdot\left(1-H^{2}\right) \\ T=\sqrt{(1-k)\left(1-\alpha_{c}\right)} \\ P^{\prime}=k\left(1-\alpha_{c}\right) \sqrt{1-\alpha_{L}} \\ P=P^{\prime} \exp \left(-\pi \Delta f_{0} \tau_{0}\right) \\ H^{\prime}=\sqrt{(1-k)\left(1-\alpha_{c}\right)\left(1-\alpha_{L}\right)} \\ H=H^{\prime} \exp \left(-\pi \Delta f_{0} \tau_{0}\right)\end{array}\right.$
Here $I_{0}$ is input intensity, $I_{\text {out }}$ is output intensity, $f$ is the input light frequency, $\tau_{0}$ is the optical transmission time in the ring. In theory, it is expressed as $\tau_{0}=n_{\text {eff }} L / c, \alpha_{c}$ is the loss of the resonator coupler, $\alpha_{L}$ is the loss of the resonator. $\Delta f_{0}$ is the spectral line-width of the laser.
$T$ represents optical direct coupling output coefficient, $P^{\prime}$ represents cross coupling coefficient of resonant cavity, $H^{\prime}$ represents single circle transmission coefficient of resonant cavity.
$\rho=\frac{x_{1}}{x_{2}}$
( $x_{1}$ is the amplitude range, $x_{2}$ is the maximum value of the resonance curve)
$F=\frac{f_{\text {FSR }}}{\Gamma}$
$\mathrm{f}_{\mathrm{FSR}}=\frac{c}{n_{\text {eff }} L}$
$Q$ factor: $\quad Q=\frac{f_{0}}{\Gamma_{f}}=\frac{\lambda}{\Gamma_{\lambda}}$
Combine Eq. (16) with Eq. (17), we can conclude that
$Q=\frac{f_{0} F}{f_{F S R}}$
$F=\frac{f_{F S R} Q}{f_{0}}$
where $\rho$ is the resonance depth, defined as the ratio between the amplitude range and the maximum value of the resonance curve, $f_{\text {FSR }}$ is the free spectral range [7], $\Gamma$ is FWHM, the full width at half maximum, $F$ is Finesse, $Q$ is quality factor of FRR.

The sensitivity $(\delta \Omega)$ of the FRR is an important parameter of gyroscope, which can be written as [6]:
$\delta \Omega \approx \frac{\lambda L}{4 A} \frac{\sqrt{2} \Gamma}{S N R}$
$S N R=\sqrt{\frac{\eta t_{0} I_{0}}{2 h f_{0}}} \frac{T_{\text {FRR_max }}-T_{\text {FRR_min }}}{\sqrt{T_{\text {FRR_max }}}}$
So according to the description of SNR, we can conclude that SNR increases with the difference between $T_{F R R \_ \text {max }}$ and $T_{F R R \_ \text {min }}$, also means that it increases with the slope of the resonance curve.

While the precise expression of sensitivity are as follows [5,8,9]: Type 1:
$\delta \Omega=\frac{3 \sqrt{3} \pi}{4} \cdot \frac{N c \lambda}{F \rho L^{2}}\left[(1-\sqrt{2 / 3} \rho) \frac{\hbar \omega}{\eta_{p d} I_{0}} B\right]^{1 / 2} \mathrm{rad} / \mathrm{s}$
Type 2:
$\delta \Omega=\frac{1}{d Q \sqrt{P_{p d}}} \cdot \sqrt{\frac{2 h c^{3}}{\tau \lambda \eta_{P D}}}\left(\frac{3600 \times 180}{\pi}\right) \circ / \mathrm{h}$

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