Overview and Improving Fiber Optic Gyroscope Based on MEMS/NEMS Fabrication

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Abstract. The measurement of the rotation of rigid solids is of considerable interest in a number of areas. Rotation detectors are not only used in aircraft, missiles etc. military fields have also been developed for new civil fields such as automobile navigation, antenna stabilization, crane control, unmanned vehicle control, wind and renewable energy platform stabilization. In this paper, the fundamental operations of fiber-optic gyroscopes are reviewed. Performance-limiting phenomena are discussed along with methods to reduce their effect on the rotation-rate signal. Current technology and performance of new demodulate systems are presented applicable to MEMS technology. The FOG with scanning phase-shift demodulates technology based on anti-noise filter circuit improvement of DSP algorithm is proposed in this paper. New methods, which are used to fabricate the nanometer optical fiber, are discussed.

Keywords: FOG, Phase-shift, DSP, MEMS, Nano, SM-PM (signal-model polarizer-maintain fiber)

1. INTRODUCTION

Detection of rotational with interference in light was demonstrated by Sagnac in 1913 [1]. He showed that two waves acquired a phase difference by propagating in opposite directions around a loop interferometer (Fig. 1), which was rotating about its axis. The effect was small, however, and measurement of slow rotations required a substantial interferometer. For example, to measure the rotation rate of the earth, Michelson and Gale used an interferometer like the one shown in Fig. 1, but
having a perimeter of over 1 meter [2]. A ring laser provides a dramatic improvement in sensitivity, allowing the use of small loops, by internally converting the phase difference to a frequency difference and measuring this frequency difference precisely. Interest in the ring laser gyroscope has continued since its first demonstration by Macek and Davis in 1963. It has been developed to the point where it is now finding practical application in inertial navigation.

An alternative and convenient method for increasing the sensitivity of passive Sagnac systems uses an optical fiber (Fig. 2) which may be wrapped many times around a small cylinder to increase the phase difference produced by rotation. Long total fiber lengths may be used because of the impressive progress which has been made in the fabrication of very low loss single-mode fibers. The first demonstration of such a system was made by Vali and Shorthill in 1976 [3]. This device has since been studied in a number of laboratories, and has progressed from being incapable of detecting the earth rotation rate to being able to detect rotation rates some three orders of magnitude below earth rate today. As a result of this, and also because of the possibility of being packaged in a small rugged form, including all-solid-state implementations, fiber gyroscopes are now of substantial interest for potential practical applications.

In the fiber gyro, the insertion of the fiber medium into the optical path of a Sagnac interferometer does not alter the Sagnac effect directly, but gives rise to spurious signals. One problem encountered is associated with birefringence in the fiber when the counter propagating waves have different states of polarization. Another problem is involved with backscattered waves in the fiber arising from Rayleigh scattering. Both of these phenomena lead to noise, instability, and drift in the signal in response to environmental effects such as vibration and thermal variations. A further problem is concerned with biasing the gyro to move its operating point from one which is insensitive to rotation to one having maximum sensitivity to rotation without, at the same time, introducing further instabilities. Proper consideration for optical reciprocity, optical source characteristics, and biasing requirements allowed fiber gyroscopes to measure below earth rate. To further increase the sensitivity to present levels, a number of other physical phenomena had to be identified and accommodated, including the Faraday Effect in the fiber material in the presence of the earth’s magnetic field and the nonlinear optical Kerr effect in the fiber material.
In contrast to conventional gyroscopes, optical gyroscopes have no rotating parts, which, generally, is an asset. They are of interest for many similar applications, including inertial navigation, guidance, and tracking, and applications based on direct determination of the earth’s rotation vector. In application, fiber gyroscopes would generally be mounted rigidly on a vehicle or object whose rotation is to be measured, and the only rotation involved is that of the vehicle itself. When used together with accelerometers, the path of a vehicle can be determined entirely from measurements made within the vehicle. Sensitive accelerometers for such purposes are also potentially realizable in a fiber-optic form.

2. Sagnac Effect Theory

In this section, the detail of the Sagnac effect would be discussed about two situations in the inertial frame. If two pulses of light are sent in opposite directions around a stationary circular loop of radius \( R \), they will traveled the same inertial distance at the same speed, so they will arrive at the end point simultaneously. This is illustrated in the left-hand Figure 3 below. [4]

![Figure 3 The Sagnac effect Principle Diagram](image)

(a) CCW and CW without Rotating (b) CCW and CW with Rotation \( \Omega \)

The Figure 3 on the right indicates what happens if the loop itself is rotating during this procedure. Supposing that radius of fiber round is \( R \), and light emitting and detector sensors are laid in ‘A’ point. The system is rotating with in the clockwise direction relatively inertia space. When clockwise direction light (CW) and the counter-clockwise direction light (CCW) are emitted in opposite direction around, the photo sensor also rotates from ‘A’ to ‘A’’. So the two light paths are different length. The clockwise direction light pursues ‘A’ after back, which crosses the distance more than \( 2\alpha R \). While the counter-clockwise direction light goes face to ‘A’, which crosses the distance less than \( 2\alpha R \). The difference between the travel times causes the difference light distance.

Now, we will look what is difference CW and CCW in mathematics.

Assume light transmitting in vacuum, which velocity is \( c \). The paths of clockwise and counter-clockwise light are \( L_{cw}, L_{ccw} \) spending time is \( t_{cw}, t_{ccw} \) individual.

\[
C = C_{cw} = C_{ccw}
\]

\[
L_{cw} = 2\pi R + R\Omega t_{cw} = C_{cw} t_{cw}
\]

\[
L_{ccw} = 2\pi R - R\Omega t_{ccw} = C_{ccw} t_{ccw}
\]

(1)

From (1), \( \Delta t \) is

\[
\Delta t = t_{cw} - t_{ccw} = 2\pi R \frac{2\pi\Omega - (C_{cw} - C_{ccw})}{C_{cw} \cdot C_{ccw}}
\]

\[
= 2\pi R \frac{2\pi\Omega}{C^2} - \frac{4\alpha\Omega}{C^2}
\]

Where \( \alpha \) is area of light circuit.
Accounting, it is only approximately and simple evolvement above result in the equation (2). The strict evolvement should be applied in broad theory of relativity. The light transmitted in fiber optical, its speed is relation with refractive index of medium.

So, clockwise and counter-clockwise light is:

\[
C_{cw} = \frac{c + n \Omega}{1 + \frac{n \cdot \Omega}{c}} = \frac{c + n \Omega}{1 + \frac{c \cdot \Omega}{c \cdot n}}
\]

\[
C_{ccw} = \frac{c - n \Omega}{1 - \frac{n \cdot \Omega}{c}} = \frac{c - n \Omega}{1 - \frac{c \cdot \Omega}{c \cdot n}}
\]

Where \( n \) is refractive index of medium. From (2), (3)

\[
\Delta t = t_{cw} - t_{ccw} = 2\pi R \frac{2n\Omega - (C_{cw} - C_{ccw})}{C_{cw} \cdot C_{ccw}} = 2\pi R \frac{2n\Omega - 2n\Omega(1 - \frac{1}{n^2})}{c^2 \frac{1}{n^2}} = \frac{2\pi R}{c^2} \frac{4\Delta \Omega}{C^2}
\]

The equation (4) is same (2) in the vacuum. Corresponding phase difference is:

\[
\Delta \phi = \frac{2\pi \Delta t c}{\lambda c} = \frac{8\pi \Delta \Omega}{\lambda c}
\]

3. Detector and New Demodulator Technology for FOG

Sensing methodologies utilized in inertial sensing generally fall under two categories: open-loop or closed-loop control architectures.

Open-loop control systems measure changes in the sense signal, whether it is a change in piezoresistance or capacitance or optoelectronics or other change, as a result of the inertial load displacing the seismic mass or rotation from its zero state position. These signals are typically amplified, compensated, filtered, buffered and output as control variables either as analog voltages or digital control signals to the larger system. Open-loop control schemes tend to be relatively immune to small production variations in the transducer element, are inherently stable systems relying on no feedback signals, provide radiometric output signals and, possibly most importantly, are often smaller in die area than their closed-loop counterparts.

![Figure 6 Open-Loop Analyzer Circuit of Light Intensity](image)
To circumvent some of the above difficulties, closed-loop approaches are being investigated. Closed-loop control schemes rely on feedback to control the position of the mass via a force feedback, or force rebalancing, at its rest position. The force feedback required is proportional to the magnitude of the inertial load. The potential for this methodology is great. Closed-loop force feedback systems have the potential for very high sensitivity and have been implemented in optic gyroscopic systems due to the minute forces. [5]

Based on closed-loop system, the new demodulator technology of FOGs would be proposed. The figure 7 shows the principle diagram of scanning phase shift FOG system. The light source of system used a super luminescent diode (SLD), light entrance the Y junction waveguide (LiNbO$_3$) through polarization maintain coupler (PM-BS). The each shoulders of Y waveguide were modulated by D/A1 and D/A2 converter controlling. One of them was used to Phase Shift Keying (PSK); the other was used to Phase Expiation Modulator (PEM). The opposite light create interference figure at PIN detector. Then the light signal was converted to voltage signal, which passed the front amplifier, noise filter, A/D (TI ADS5422), and putted into DSP (TI TMS320), which took charge creating the modulator wave and calculating the difference phase of interference.

Figure 7 Scan Phase Shift FOG Systems

The basic theory of scanning phase shift demodulator was described below:
Assuming the interference signal only contained the Sagnac phase shift $\phi_s$, and added the random noise $n(t)$. Then the interference signal $I(t)$ was:

$$I(t) = I_0 + aI_0 \cos(\phi_s) + n(t)$$

Importing PSK modulator: $\phi_m = 2\pi kt$

Then, the interference signal is

$$I(t) = I_0 + aI_0 \cos(\phi_s + \phi_m) + n(t)$$

Using modulator phase $\phi_m$ sine and cosine integral operation:

$$A = \lim_{N \to \infty} \int_0^N I(t) \cdot \sin(2\pi kt) dt = K a \cdot I_0 \cdot \sin(\phi_s)$$

$$A = \lim_{N \to \infty} \int_0^N I(t) \cdot \cos(2\pi kt) dt = K a \cdot I_0 \cdot \cos(\phi_s)$$

Get $\phi_s = \tan^{-1}(\frac{A}{B})$
$N$ is the numbers of processing cycle. $T$ is cycle of the modulator. In the result (11) of difference phase, the noise effect has been eliminated or restrained. So this demodulator method is good at restrain the system noise, and not sensitive contrast of interference intensity. [6]

This new demodulator method not only overcome weakness the measurement of open-loop is sensitive non-linear and contrast of interference intensity, but also the lock-in effect in close-loop measurement. So this method could gain high precision, linear, stability etc.

4. MEMS FOG Miniaturization Based on New Fabrication Nano-Level Optic Fiber

Now, the researcher at the University of California has discovered a way to turn spider silk into the world’s finest optical fibres. I proposed a MEMS FOG system based on this new technology. Under the MEMS fabrication, the nano-level light source and micro mirror and coupler would be done by micromechanical technique. If the nano-scale optical fibre would be applied in the MEMS FOG system, then the one chip FOG should be born. This micro FOG system will be applied in the micro robot, unmanned air-vehicles etc. in nicety foreground.

The inventor glued a length of spider web between two bits of cardboard, and then dipped it repeatedly in a solution of tetraethyl orthosilicate. Once the silk was well coated, it was fired at 420°C. At this temperature the entire spider silk burned away completely, while the tetraethyl orthosilicate was set into solid silica glass. The resulting hollow glass tube is actually narrower after firing, shrinking five-fold in the furnace. Given this shrinking, if the thinnest spider silk known was used, the silk of the spider stegeodyphus pacificus, a native of the Middle East and South Asia, then it could produce an optical fibre just two nanometres wide (50,000 times thinner than human hair). That is more than ten times smaller than that produced by conventional methods.

Certainly, this method also has the disadvantage. The major hold-up in this technology is being able to get large quantities of spider silk. We cannot synthesize it yet, and farming it is also impractical. The real system wants to be completed for several years.

5. Conclusion

In this paper, we have seen that an optical fiber has been used to substantially increase the Sagnac phase difference due to rotation. This phase difference has then been measured accurately by making use of reciprocity and dynamic biasing technique and by removing the effect of environmentally induced dynamic variations in the system acting alone and together with Rayleigh backscatter, the Faraday Effect, and the optical Kerr effect. We have reviewed the technology involved in making these systems in hybrid and all-guided forms. The new demodulator technology was proposed and explained the advantages. It is possible the MEMS technology and nano-level optical fiber combined with FOG system would be discussed. The further works are set up the FOG system to compare the different demodulator methods, and applied the MEMS fabrication to decrease the physical size of FOG system. Finally, the nano-scale FOG should be developed.
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