論文の内容の要旨

論文題目　Studies toward the Realization of Resonator Fiber Optic Gyro with All Digital Signal Processing
（全ディジタル信号処理を指向した共振型光ファイバジャイロの実装法と性能向上）

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A gyro is a device that can measure the angular velocity with respect to an inertial frame. A fiber optic gyro (FOG), specifically, detects the rotation by measuring the Sagnac effect induced phase difference between the clockwise (CW) and counter clockwise (CCW) lightwaves that propagate inside a closed-loop formed with an optical fiber. FOGs have been under intense research and development since the 1970s, due to the fast development in low-loss optical fiber, solid-state semiconductor light source, and other optical components for telecommunication applications. FOGs show significant advantages over traditional spinning gyros with gimbals, bearings, and torque motors, especially in the aspects of short warm-up time, reliable operation, wide dynamic range, low power consumption, and etc. As a result, the FOG has paved its way for many successful commercial applications, such as aircraft navigation, rocket control, ship navigation, and etc. However, the applications are limited to the industrial grade (>10 ^{o}/h) and the inertial navigation grade (0.01~10 ^{o}/h). To produce superior grade models with sensitivity better than 0.01 ^{o}/h, further research about the FOG is needed.

There are three major types of FOGs: the interferometer fiber optic gyro (I-FOG), the resonator fiber optic gyro (R-FOG), and the Brillouin fiber optic gyro (B-FOG). The I-FOG measures the rotation by detecting the intensity of the interference signal between the two counter propagating lightwaves. The R-FOG, which utilizes a high finesse resonator as the sensing component, gauges the rotation by measuring the resonant frequency difference between the CW and the CCW lightwaves. The B-FOG extracts the rotation information by determining the lasing frequencies of two essentially independent counter propagating Brillouin lasers.

Although the I-FOG has achieved the highest performance among the three types of FOGs up to now, it suffers an inherent problem resulted from its use of a long fiber (~ km). Performance degradation due to the time-variant temperature distribution along the long fiber, called as the Shupe effect, becomes a bottleneck for the I-FOG's further upgrade. Besides, the wavelength stability and light intensity of semiconductor superluminescent diodes and fiber type broad-band light sources, which are used as I-FOGs' light sources, are inferior to laser sources. The R-FOG and the B-FOG, on the other hand, may have the capability to solve the inherent problems in the I-FOG. For example, theoretical analyses estimate that a 5 to 10 m long fiber is enough for the R-FOG to satisfy aircraft navigation requirement.

In practice, however, the performances achieved up to now for both the R-FOG and the B-FOG are still below expectation. For the R-FOG, countermeasures against performance degradation factors, such as the polarization-fluctuation induced drift caused by the existence of dual eigen-states of polarization (ESOP) in the resonator and by temperature-sensitive birefringence of the fiber, the backscattering, the optical Kerr effect caused by the nonlinearity of the fiber, the Shupe effect caused by temporally variant temperature distribution along the fiber coil, the Faraday effect, and other external fluctuation induced drifts, have to be further studied. For the B-FOG, the "lock-in" phenomenon, which indicates a zero output when the rotation rate is very small, and the instability of the lasing frequency are pointed out as major drawback that limit the performance of the B-FOG.

For the R-FOG, the recent advent of air-core photonic-bandgap fibers (PBFs) offers a radically new means for further reducing all of the above performance degradation factors simultaneously, as in a PBF the optical mode is mostly confined to the air core, whereas in a conventional fiber, the lightwave travels entirely through silica. Thus, by replacing the solid-core fiber with the PBF in the R-FOG, the R-FOG is still a promising candidate for high grade rotation sensing. Yet, before the PBF-based optical components are available, there still exist constant drives for further investigation and invention of engineering solutions for the remaining performance degradation factors.

As a countermeasure against multiple performance degradation factors in the R-FOG, a bipolar digital serrodyne phase modulation scheme has been invented. In this scheme, the laser frequency is locked to the resonant frequency of one of the CW or CCW sides by synchronously detecting the frequency component that the bipolar digital serrodyne waveform changes its slope with. Determined by the absolute value of the slope of the bipolar digital serrodyne waveform, the laser frequencies of the CW and the CCW sides can be shifted to different frequency bands such that the intensity contribution by the backscattered lightwave goes out of the detection band. Moreover, by precisely adjusting the amplitude of the bipolar digital serrodyne waveform to exact 2π, the interference signal between the CW and the CCW lightwaves is removed due to the suppressed carrier lightwave. Additionally, by modifying the slope of the bipolar digital serrodyne waveform, the intensity of the injected lightwaves can be adjusted; thus, the optical Kerr effect induced performance degradation is alleviated. Finally, the closed-loop operation can be achieved by using the bipolar digital serrodyne waveform adding an additional digital serrodyne waveform with smaller slopes to the original one to shift the laser frequency.

Most of above functions of performance degradation suppression realizable by the bipolar digital serrodyne phase modulation scheme call for the precise control of the waveform and careful designing of peripheral signal processing circuits. Up to now, they are realized by analogue or partially analogue circuits, which lack in accuracy, processing speed and convenience. Meanwhile, during the past decades, digital signal processing techniques have undergone tremendous developments, especially the field-programmable gated array (FPGA) technologies have exhibited higher precision, faster handling speed, and easier transforming to other platforms than the analogue circuits. Thus, in this thesis, to improve the performance of the R-FOG, the performance degradation factors in the R-FOG are studied, with countermeasures proposed and experimentally demonstrated by implementing an FPGA-based digital signal processor.

The structure of the thesis is stated below.

At first, the history of fiber optic gyros is reviewed in Chapter 1. Two important classes of gyros, the optical gyro and the MEMS gyro, are introduced. By studying the working principles, investigating the performance-limiting factors, and exploring the up-to-date applications, comparisons are drawn between several types of gyros. The study indicates that gyros are driven for technological breakthroughs towards improved stability, lower cost, smaller size and lighter weight. Besides, the purpose and the constitution of the thesis are also stated.

Next, the performance degradation factors in the R-FOG are summarized in Chapter 2, including the polarization fluctuation, the backscattering, the optical Kerr effect, the thermal fluctuation, the Faraday effect, and other external fluctuations. The corresponding engineering countermeasures are also presented. However, these elegant engineering solutions are not perfect. The performance achieved is still not satisfying. Thus, there is a trend to study the PBF-based R-FOG.

In Chapter 3, a passive method to suppress the polarization-fluctuation induced performance degradation using twin 90^o polarization-axis rotated splicing scheme is analyzed, with the effect demonstrated experimentally. To begin with, the physical image of the eigen-state of polarization (ESOP) in R-FOG is introduced. Then, the principle of selective excitation of single ESOP in R-FOG with twin 90^o polarization-axis rotated splicing is shown mathematically. Next, the polarization-fluctuation induced bias drift is estimated, especially for the case when polarization dependent loss (PDL) exists inside the resonator. Simulation results indicate that the twin 90^o polarization-axis rotated splicing method can effectively suppress the polarization-fluctuation induced bias drift in the R-FOG, when the length difference of the fiber segments between the two splicing points (Δl) is set around a half of the beat-length of PMF ($B/2$). It is also shown that such an R-FOG is tolerant to PDL if the polarization crosstalk in the resonator is low. Then, experiments to demonstrate the effectiveness of the twin 90^o polarization-axis rotated splicing method in suppressing the polarization-fluctuation induced performance degradation are carried out. A single ESOP is selectively excited for the first time using this method. Besides, significantly suppressed bias drift is observed with selective excitation of a single ESOP.

Then in Chapter 4, a method to automatically suppress the polarization-fluctuation in the R-FOG is proposed by adopting a resonator with twin 90^o polarization-axis rotated splicing. Both theoretical analysis and experimental results demonstrate the effectiveness of the method. As shown in Chapter 3, to effectively suppress the polarization-fluctuation induced bias drift in the R-FOG, the length difference of the fiber segments between the two splicing points of an R-FOG with twin 90^o polarization-axis rotated splicing should be set around a half of the beat-length of PMF. Although this ideal condition can be realized at the startup of the system, long term preservation cannot be guaranteed due to varied temperature around the fiber coil and the temperature sensitivity of the birefringence in PMF. To achieve high long-term bias stability, a scheme that can monitor the variation of Δl and hence suppress the polarization-fluctuation induced performance degradation is proposed, in which a feedback scheme is built up to fix Δl to $B/2$ to excite the wanted ESOP only (linear and polarized along the x-axis of PMF) with the error signal generated by inserting a y-axis polarizer in one output branch of the resonator. After demonstrating the effectiveness of the proposal numerically with a mathematical model based on Jones transfer matrix, experiments are carried out to compare the gyro bias drifts with the control loop on and off. Experimental results indicate that the bias stability is increased with polarization-fluctuation induced drift suppressed significantly.

In Chapter 5, the implementation of digital signal processing based on FPGA is introduced. At first, an overview of the multiple functions realized by the digital processor is presented. Then, as one of the functions, suppression of R-FOG performance degradation due to backscattering using the digital processor is discussed in detail. The digital processor is designed to automatically adjust the amplitude of the bipolar digital serrodyne phase modulation waveform applied to the CW and CCW lightwaves to exact 2π. Experimental results indicate significant suppression of bias drift resulted from the backscattering. Moreover, improved bias stability is realized experimentally by incorporating oversampling technique into the digital signal processing system. Further improvement is achieved with a newly proposed lock-in detection scheme using 90^{o} out-of-phase reference signal.

Next, suppression of other external fluctuations induced performance degradation using the self-developed digital signal processor is shown in Chapter 6. The difference between the laser frequency and the resonator's resonant frequency fluctuates in two ways: the fast drift with small amplitude and the slow drift with large amplitude due to the thermal fluctuation and/or the mechanical vibration. The digital processor serves to suppress the fast-drift by a proportional controller with oversampling technique to reduce the quantization error and to track the slow drift using an up/down counter. Experimental results demonstrate the effectiveness of the digital processor in stabilizing both kinds of fluctuations. Improved laser frequency tracking precision by removing higher harmonic frequency noises is also realized experimentally.

As a final demonstration, a closed-loop R-FOG with all digital signal processing is presented in Chapter 7. The system adopts the bipolar digital serrodyne phase modulation scheme as a countermeasure against multiple performance degradation factors in the R-FOG. The FPGA based digital processor realizes not only the full operation of the bipolar digital serrodyne waveform but also other signal processing functions. The closed-loop operation is realized by adding an additional bipolar digital serrodyne waveform to the original waveform to maintain the laser frequencies of both the CW and the CCW sides operating at the resonator's resonant frequency.

Finally, the conclusions and the future prospects of the R-FOG are stated in Chapter 8.