A large scale passive laser gyroscope for Earth rotation sensing

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(Dated: 18 January 2019)

Rotation sensing of Earth has many applications in different disciplines, such as monitoring of ground motions, the establishment of UT, and the test of the relativistic Lense-Thirring effect. We report the development of a large scale passive resonant gyroscope (PRG) with a meter size optical ring cavity. By locking a pair of laser beams to adjacent modes of the square ring cavity in the clockwise and counter-clockwise directions, we achieve a rotation resolution of $7 \times 10^{-10}$ rad/s at an integration time of 4000 s. The PRG detects the tiny rotation motions of the housing platform, and the rotation sensitivity reaches a level of $2 \times 10^{-9}$ rad/s/$\sqrt{\text{Hz}}$ in the 5-100 Hz region, currently limited by the detection noise, residual amplitude modulation and the instability of the cavity length. Our result improves the rotation sensitivity of the PRGs to a new level, and indicates that PRGs have a great potential to be a high resolution Earth rotation sensor at much smaller cost.

Keywords: ociscodes(120.3940) Metrology; (120.5790) Sagnac effect; (140.2020) Diode lasers; (140.3370) Laser gyroscopes; (140.3410) Laser resonators.

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I. INTRODUCTION

Many large scale ring laser gyroscopes (RLGs) have been built over the last three decades with extremely high sensitivity and excellent stability\(^4\). These large ring lasers have found applications in different fields like geophysics\(^2,13\), geodesy\(^3\), seismology\(^4\), and fundamental physics tests\(^5,6\). The G-ring at the Geodetic Observatory of Wettzell in Germany, the most sensitive large RLG, has a shot-noise limited sensitivity of 11 prad/s/\(\sqrt{Hz}\). Taking advantage from its monolithic structure design and superior environmental control, it can resolve a rotation rate of \(3.5 \times 10^{-13}\) rad/s over 1000 s of integration time\(^12\) and detects the Chandler and the annual wobble of the Earth\(^7\). Two really large RLGs (UG-1, UG-2) have been built by University of Canterbury in New Zealand with enclosed areas of 367 m\(^2\) and 834 m\(^2\), respectively\(^8,9\). Their operation verifies the feasibility of constructing giant rotation sensors but also proves that better stability control of the enclosed area is required to realize the potential sensitivity. A 1.96 m\(^2\) ring RLG called G-Pisa has been constructed by University of Pisa in Italy to improve the active seismic isolation system for gravitational-wave antenna Virgo. It has a sensitivity in the range between \(10^{-8}\) and \(10^{-9}\) rad/s/\(\sqrt{Hz}\)\(^10\). After that, an ambitious plan named GINGER has been proposed by University of Pisa, INFN, and other collaborate institutions, with the aim of measuring the Lense-Thirring effect in a terrestrial laboratory\(^11\). In 2016, Korth et al. report a passive resonant laser gyroscope (PRG) with a side length of 0.75 m, which is used as a tilt sensor to augment the active suspension control system in LIGO. It has a sensitivity of \(10^{-8}\) rad/s/\(\sqrt{Hz}\) above 0.5 Hz\(^14\). In 2017, a tetrahedron-shaped 3-dimensional RLG with sides of 12 m named ROMY is constructed by Ludwig Maximilian University and other collaborators. It is believed that it will bring great progress in rotational seismology and it eventually may have the potential to measure the Lense-Thirring effect\(^4\).

The measurement principle of RLGs is based on the Sagnac effect: the counter propagating laser beams in a ring cavity will see a different round trip length if the ring cavity is rotating in the optical plane. This effect was first described by Sagnac in 1913\(^15\). The earlier design of the device is a phase-sensitive interferometer. In 1963, Macek and Davis utilized a ring cavity that contains He-Ne gas to lase at the 1.153 \(\mu\)m line, which was used as a high performance rotation sensor\(^16\). This is considered to be the first active RLG. Another type of gyro was proposed and realized by Ezekiel and Balsamo in 1977 as a PRG\(^17\). An external
laser is split into two beams and locked to a passive ring cavity in the clockwise (CW) and
counter-clockwise (CCW) directions. The rotation rate can be determined by measuring
the resonance frequency difference of the ring cavity in the opposite directions. There are
many PRGs under development by different research institutes, aiming for high sensitivity
rotation rate detection\textsuperscript{14,17–21}.

The principles of an active RLG and a PRG are the same: the resonant frequency differ-
ence of the ring cavity in the opposite directions is proportional to the rotation rate of the
cavity frame itself, and can be written as:

\[
fs = \vec{K} \cdot \vec{\Omega},
\]

where \(fs\) is the resonant frequency difference, called Sagnac frequency, \(\vec{\Omega}\) is the rotation
rate vector, and \(\vec{K} = 4\vec{A}/\lambda P\) is the scale factor, where \(\vec{A}\) is the area vector enclosed by the
cavity, \(P\) the cavity perimeter and \(\lambda\) the laser wavelength. The main difference between an
active RLG and a PRG is that the former has a lasing medium inside the cavity, while the
latter utilizes an external laser to be injected in. Both of them have their own advantages
and disadvantages. However, it is believed that they have essentially the same ultimate
sensitivity, which is limited by the cavity loss\textsuperscript{22,23}. But so far the performance of a PRG is
still worse than that of an active RLG\textsuperscript{14,17–21}, so it is worth to revisit these experiments to
look for other limiting factors and trying to improve technologies further.

In this Letter, we report a PRG utilizing a diode laser locked to adjacent longitudinal
modes of a 1 m\(^2\) ring cavity with a detection noise limited performance. This is a prototype
of the PRG that is under development in our group with the ultimate goal of developing a
PRG that can be used for Earth rotation monitoring to support the space-borne gravitational
wave detector TianQin\textsuperscript{24}. With suppression of the residual amplitude modulation (RAM),
laser power fluctuation, and the backscattering effect, we achieve a rotational sensitivity of 2
nrad/s/\(\sqrt{\text{Hz}}\) between 5 to 100 Hz, which is mainly limited by detection noise. By monitoring
and deducting cavity length drift, a relative Allan deviation of the Sagnac frequency of
\(1 \times 10^{-5}\) is obtained at a integration time of 4000 s, which corresponds to a rotation rate of
\(7 \times 10^{-10}\) rad/s. To our knowledge, this is the best result reported in a PRG, demonstrating
the great potential of high sensitivity large scale passive gyroscopes.
II. EXPERIMENTAL APPARATUS

The experimental setup is shown in Fig. 1. An 1064 nm diode laser (Toptica, DLCpro) is split into two branches, and phase modulated by two fiber electro-optic modulators (EOM). The two modulated laser lights are mode matched, then coupled into the ring cavity in the CCW and CW direction and locked to the ring cavity with the Pound-Drever-Hall (PDH) technique\textsuperscript{25}. The two locking loops are named the primary and the secondary loop, respectively. The secondary loop is frequency shifted by a fiber acoustic-optic modulator (AOM) to maintain a frequency lock with an offset of nominally one cavity free spectral range (FSR). The high $Q$ factor 1 m×1 m square ring cavity is made from 4 super mirrors with a reflectivity of 99.999\% at 45° incident angle and 3 m radius of curvature. We achieve a cavity finesse of about 141,000 with a measured ring-down time of about 300 $\mu$s. It indicates a high $Q$ factor of $5.3 \times 10^{11}$. In order to isolate the air flow, the ring cavity is placed in a vacuum chamber with a pressure of $2 \times 10^{-6}$ Pa. Instead of a traditional optical table, a granite platform with a weight of 2.7 ton is used to hold the chamber with enhanced dimensional stability. Our PRG is placed inside a cave laboratory to isolate the vibration and temperature fluctuation of the environment. In order to reduce the RAM effect of the EOM in the PDH locking, two RAM PDs are used to monitor the RAM at the modulated frequencies in the CCW and the CW loop, and we then actively stabilize the RAM fluctuations. Behind the cavity, a Mach-Zehnder heterodyne interferometer and an avalanche photodiode (APD) is utilized to sense the laser frequency difference of the primary and secondary loop. In a PRG, a faithful cavity locking is essential to achieve a good sensitivity. To obtain a high signal-noise ratio (SNR) of the PDH error signal, we take great care of the mode matching of the TEM$_{00}$ mode into the ring cavity. Since the cavity is made of 4 identical curved mirrors, we measure the Gaussian beam parameters of the leaked light from the cavity by a beam profiler (Dataray, WinCamD). The measured data is then used as a guidance for the mode matching telescope design. We then achieve a mode overlapping ratio of 70\% for both locking loops.

Since the linewidth of the free-running diode laser is about 500 kHz, in order to lock the laser to the ring cavity in the primary loop, we implement a two-branch feedback control to the diode laser. The fast feedback branch is set by controlling the current and has a bandwidth of 1.5 MHz. The slow feedback branch uses a piezo with a locking bandwidth of
FIG. 1. Experimental scheme of the PRG. AOM, acoustic-optic modulator; EOM, electro-optic modulator; RAM PD, photodiode for residual amplitude modulation detection; PDH PD, photodiode for PDH locking; LIA, lock-in amplifier; VCO, voltage controlled oscillator; APD, avalanche photodiode; Ref. Laser, an ultra-stable laser as a reference to diagnose the ring cavity displacement noise.

around 5 kHz. It increases the low frequency gain to ensure that the laser follows the cavity length drift. Ultimately, a servo feedback gain of 140 dB from DC to 1 Hz has been obtained via the piezo feedback branch. In the secondary loop, the AOM is used as the actuator to accomplish the locking loop by driving a voltage controlled oscillator (VCO). The driving frequency is denoted as $f_{AOM}$. In our case, $f_{AOM}$ is approximately 75 MHz to match the FSR of the square ring cavity.

The Sagnac frequency, $f_s$, which is related to the rotation rate of the PRG, can be obtained from the beat frequency of the heterodyne interferometer:

$$f_s = f_{AOM} - f_{FSR}. \quad (2)$$

The beat frequency equals to $f_{AOM}$, which contains the rotation rate $f_s$ and the FSR frequency of the cavity $f_{FSR}$. 
III. RESULTS AND DISCUSSION

The ring cavity length change is a common mode noise if the CW and CCW modes see the same cavity frequency. The device operates in a split mode with a FSR frequency separation for the CW and CCW modes. In this way, the cavity length drift is a major noise source for our rotation sensor. In our case, the common mode rejection ratio, $CMRR$, is the ratio of the laser frequency to the frequency difference of the two loops, $CMRR = \nu_l / f_{AOM}$. Therefore, we monitor this cavity displacement noise by measuring the resonant PRG laser frequency variation of the primary loop via an ultra-stable laser reference. The ultra-stable laser has a frequency instability of $8 \times 10^{-16}$ and a drift rate of $3$ kHz/day$^{26,27}$. We record the

![Graphs showing detected Sagnac frequency and PRG laser frequency variation.](image)

FIG. 2. (a) The detected Sagnac frequency is shown with a blue curve, and the resonant PRG laser frequency variation of the primary loop measured with an ultra-stable laser source is shown with a red curve. (b) The corrected Sagnac frequency after removing the cavity drift contribution.
Sagnac frequency and the resonant PRG laser frequency of the primary loop with frequency counters (Keysight, 53230A), simultaneously. The results are shown in Fig. 2 (a) after removing common linear drifts. It demonstrates a strong correlation between the cavity drift and the Sagnac frequency. We use a least mean squares adaptive filter to the Sagnac frequency, using the PRG laser frequency as the reference signal. The residual rotation signal is shown in Fig. 2 (b). According to Fig. 2 (b), we draw the relative Allan deviation of rotation signal and show the result in Fig. 3. The Allan deviation shows a $1/\sqrt{\tau}$ slope starting from 10 s, indicating a dominant white frequency noise. We achieve an ultimate resolution of $7 \times 10^{-10}$ rad/s in rotation rate detection at an integration time of 4000 s.

![Graph](image)

FIG. 3. Allan deviation of the Sagnac frequency. A relative value to the Earth rotation rate is shown in the right vertical axis.

To further diagnose the noise contributions in our PRG, we measure the frequency noise spectrum of the Sagnac frequency in a large frequency range. The high frequency phase noise is measured with a phase noise analyzer (R&S, FSWP26), and the low frequency noise is recorded by the frequency counter. The Sagnac frequency noise is then converted to the rotational noise calibrated by the scale factor $\vec{K}$. The result is shown in Fig. 4 with a red curve. As can be seen, the PRG reaches its best sensitivity of $2 \times 10^{-9}$ rad/s/$\sqrt{\text{Hz}}$ in the $5 \sim 100$ Hz frequency range. The three peaks in rotation signal around 20 Hz are found
to be consistent with the vibration data recorded by a seismometer (Guralp, CMG-3ESP). They are induced by the oscillations and the torsion of the granite table. In other words, the tiny rotations of the heavy granite platform with several tons of weigh are observed with ultra-low noise, since the gyroscope is sensitive to rotational motion only, while the seismometer is sensitive to translational motion. In order to obtain theoretical estimations

FIG. 4. The linear power spectrum density of the gyroscope output and the estimated noise contributions. The red line is our PRG sensitivity performance, the blue line is the measured RAM effect contribution including electronic noise in the PDH detection, the cyan line is the calculated noise floor in the PDH detection and the pink line is the calculated noise from the APD, and the black line is the sum of the cyan and pink lines.

of the noise contributions for the rotational signal in the red curve in Fig. 4, we measure the discriminator slopes in the two PDH locking loops as a key parameter. They are obtained by feeding a square wave modulation signal to the error signal of one loop, while the other loop is locked as a reference. The beat frequencies of the two beams result in a square wave shape similar to the modulation signal. As long as the laser frequencies are near the resonance of the cavity, it shows a linear frequency response. The discriminator slope of both loops are measured to be approximately 1.2 mV/Hz when the power hitting the PDH PD is about
We then calculate the contribution of the PD detection noise based on our real locking parameters in the PDH locking loop. The PDH PD has a noise equivalent power (NEP) of 8 pW/√Hz at the modulated frequencies. The total contribution of the shot noise and electronic noise can be calculated to be $1 \times 10^{-6}$ V/√Hz, taking into account of the quantum efficiency, the PD responsitivity, and the cavity transfer function. Meanwhile, the rotational noise is dominated by the shot noise and electronic noise on the APD behind the ring cavity at above 100 Hz. In our case, the NEP of the APD is 2.75 pW/√Hz, and the detected power is about 2 µW. With the measured discriminator slope, we can convert all the voltage signals into rotation rate equivalent signals, as shown in Fig. 4. The theoretical PDH PD detection noise and the APD detection noise are shown with the cyan and pink lines, respectively. The sum is shown with the black line, which overlaps with our result very well in the high frequency region. Furthermore, we directly measure the RAM effect contribution including electronic noise in the PDH detection, and show it in Fig. 4 with a blue curve. In this measurement, the RAM effect causes the drift at low frequencies. As can be seen, the theoretical and the experimental results match well with the real obtained rotation signal, indicating the current limitations for our PRG are the locking, the RAM effect, and the detection noise.

In conclusion, we have developed a large-scale PRG, which has a sensitivity of $2 \times 10^{-9}$ nrad/s/√Hz, and we achieve a resolution of $7 \times 10^{-10}$ rad/s for a rotational signal over a integration time of 4000 s. The gyroscope has detected the tiny rotational motions of the platform that is housing the apparatus, and currently the rotational sensitivity is limited by the detection noise of the PDs, the RAM effect, and the instability of the cavity length. To our knowledge, this is the best result among all large scale PRGs. This indicates that PRGs have great potential to be a high resolution Earth rotation sensor at much smaller cost. Better performance are expected with better custom-designed photo detectors, and lower shot noise limit with increasing laser powers. In the future, we plan to use an ultra-stable laser as our light source and increase the side arm length. The advantage of using an ultra-stable laser is that it can serve as length standard to stabilize the geometrical scale factor of the PRG, with the obvious advantage of long-term stability. With all these improvements, the performance of the PRGs can have much better performance in both short-term and long-term.
The project is partially supported by the National Key R&D Program of China (Grant No. 2017YFA0304400), the National Natural Science Foundation of China (Grant No. 91536116, 91336213, and 11774108), and China Postdoctoral Science Foundation (Grant No. 2018M642807).

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