Gas Laser Frequency Control for Passive Cavity Ring Gyros

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The frequency stability of a helium-neon laser can be significantly enhanced by locking the laser's frequency to a resonance of an optical cavity. This frequency stabilization is achieved by electronic feedback and sensor control of the laser's cavity length and discharge current. The frequency locking technique described in this paper may be applied to passive resonant ring gyros and toward improving frequency standards and length measurements. When this technique was applied to a 169 cm² passive cavity, we obtained a random error of 0.0078 Earth rate units with a 10 s averaging time. Although the performance of this instrument is about one order of magnitude above the shot noise limit, extrapolation of this performance to proposed large passive resonant ring gyros indicates the desired sensitivity for precision rate sensor testing, geophysical investigations, and relativity experiments is attainable.

Nomenclature

A = area enclosed by the resonant cavity
A/O = acousto-optic modulator
c = velocity of light in a vacuum
ERU = Earth rate units (rotation rate relative to the rotation rate of the Earth)
f_m = modulation frequency of the cavity path length
I_c = intensity of light energy stored within the cavity
I_r = intensity of light energy reflected off the input mirror
I_t = intensity of light energy transmitted through the cavity
LIA = lock-in amplifier
N = number of photons per second impacting the photodetector
n = an integer
P = optical path length of the resonant cavity
PRRG = passive resonant ring gyro
PZT = piezoelectric transducer
RLG = ring laser gyro
VCO = voltage controlled oscillator
Γ = optical bandpass of the resonant cavity
λ = wavelength of the light source
η = efficiency of the photodetector
τ = averaging time for data collection
Ω = rotation rate about the normal to the plane of the ring cavity
Δf = frequency difference between the counter-rotating resonant beams
ΔI = intensity difference between the counter-rotating resonant beams
ΔZ = phase shift of the fringe pattern in a Sagnac interferometer

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Introduction

REQUIREMENTS exist for reliable rotation sensors that possess wide dynamic range and exhibit sensitivities on the order of 10^{-7}–10^{-10} Earth rate units (ERU).[1,2] Mechanical gyroscopes generally outperform ring laser gyros (RLG) when comparing drift rates and sensitivity; however, mechanical gyroscope technology has had over 75 years to mature. RLG technology, on the other hand, is relatively new and has the potential for surpassing mechanical systems in both sensitivity and (especially) system reliability.

Ring laser gyros have matured to the point of being used in primary inertial navigation systems onboard aircraft.[3] Advantages of RLG's over their mechanical counterparts include instant start-up, increased reliability, and strap-down capability. Their primary disadvantage is due to a phenomenon that limits their performance for near-zero rotation rates.[4] Although this lock-in problem has been compensated for by dithering the RLG above the lock-in threshold (and in other ways), dithering introduces complexity, injects significant noise sources, and makes it impractical to increase the size of the gyro. This and other problems associated with the presence of the laser gain medium within the resonant cavity discourage the active RLG for high-sensitivity applications.

Another approach to optical rotation sensors is the passive resonant ring gyroscope (PRRG).[5-7] Although more difficult than the RLG to implement, this instrument avoids the lock-in behavior caused by the presence of a gain medium inside the sensing ring. Back-scatter from the cavity mirrors is inevitable and results in a small level of coupling between the counter-rotating modes. Recent experimental results indicate that this leads to lock-in behavior in a passive cavity gyro.[8] Unfortunately, the narrow bandpass optical cavities required for high sensitivity are not compatible with commercially available frequency stabilized lasers, because the laser's frequency spectrum is too broad. This can limit the performance of the PRRG due to a poor signal-to-noise ratio.[9] In this paper, a unique design for a PRRG is presented, whereby the output frequency spectrum of a He-Ne laser is narrowed by locking the laser to a 26,000 Hz bandpass, 169 cm^2 optical resonant cavity. A resulting random error of 0.0078 ERU has been achieved for an averaging time of 10 s. Extrapolation of this technique to a much larger PRRG shows promise for applications requiring high sensitivity, wide dynamic range, and low system failure rate.

Background

In 1913, Sagnac demonstrated the first optical rotation sensor.[10] His concept involved propagating beams of light in opposite directions around a closed path and measuring the round-trip path length difference resulting from the instrument's rotation with respect to inertial space. In Sagnac's original design, the counterpropagating beams made one circuit of the apparatus (in opposite directions) and were brought together to form a fringe pattern on a photographic plate. By rapidly spinning this apparatus (which was mounted on a turntable), Sagnac was able to detect a very slight (0.07 fringe spacing) shift in the position of the fringes. The equation he derived for this effect was[10]

$$\Delta Z = (4A/\lambda c)\Omega \qquad (1)$$

From this equation, three alternatives are seen for enhancing the sensitivity of the Sagnac effect: 1) the enclosed area A must be made very large, 2) the operating wavelength must be drastically reduced, or 3) the experiment must be capable of resolving very small ΔZ. The first alternative allowed Michelson and Gayle to detect the Earth's rotation by the Sagnac effect.[10] Exploiting the other two alternatives has not been practical because a short wavelength radiation source has not been developed nor has it been possible to significantly reduce the resolvable fringe shift. However, the invention of the laser has changed this situation.

The laser has, in fact, provided for a different method of sensing the rotation of a Sagnac device. Instead of measuring the minute fringe shifts, a resonant ring cavity (either active or passive) can be established resulting in a rotation-rate-dependent difference in the resonance frequency between two counterpropagating beams.

The origin of this difference (or beat) frequency can be understood by referring to Fig. 1 and recalling that the resonant condition is satisfied for an optical cavity when $p = n\lambda$.[11] In a nonrotating cavity, p is determined by the sum of the geometric distances between the cavity mirrors times the index of refraction of the medium between the mirrors. However, if the cavity is rotating in the same (opposite) sense as the cavity radiation, p is slightly increased (decreased) due to the rotation of the device with respect to inertial space.

By injecting light (whose frequency can be independently controlled) into a closed cavity so that one beam travels clockwise and another beam travels counterclockwise, the frequencies of each of the beams can be respectively matched to the clockwise (CW) and counterclockwise (CCW) cavity resonances. The frequency difference Δf (in hertz) between the CW and CCW resonances is proportional to the inertial rotation rate and is given by[4]

$$\Delta F = (4A/\lambda P)\Omega \qquad (2)$$

The minimum resolvable frequency difference now becomes important in determining the utility of this concept as a high-resolution rotation sensor. This resolution limit is determined for PRRG's by the uncertainty in matching the laser

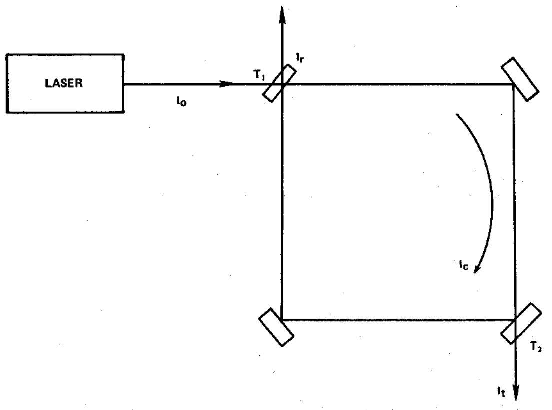

Fig. 1 Cavity at resonance.

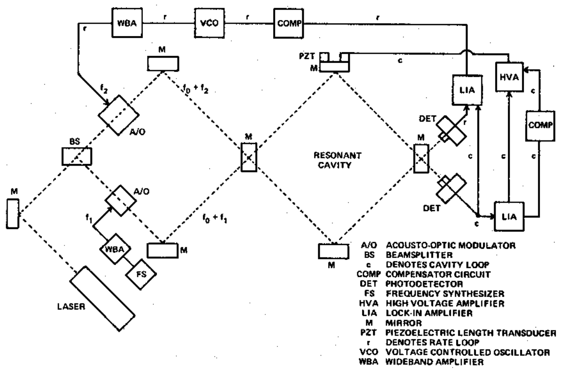

Fig. 2 Traditional passive resonant ring gyro.

frequency to the cavity resonant frequencies. If the control mechanisms driving the laser frequencies to the cavity resonant frequencies are functioning properly, the major error source is then due to shot noise. This shot noise (fundamental) limit in determining the uncertainty in the measurement of rotation rate $\delta\Omega$ has been shown to be[5]

$$\delta\Omega = \sqrt{2}\,\Gamma/(N\eta\tau)^{\frac{1}{2}} \qquad (3)$$

From Eqs. (2) and (3), to increase the sensitivity or to lower the shot noise limit, two practical alternatives arise: the A/P ratio can be increased or the cavity linewidth can be narrowed.

Traditional PRRG

The traditional PRRG exploits the Sagnac effect by measuring the frequency difference between the counterrotating beams kept in resonance with the cavity. Because the frequency difference may be only a few hertz, direct measurement of this value is not practical. An indirect method is made possible due to the fact that when light is in resonance with a cavity (as illustrated in Fig. 1), the transmitted intensity I_t is maximized and nearly equal to the incident light intensity I_c, and the reflected intensity I_r is minimized.[11] Therefore, the counterrotating beams can be kept in resonance by driving the transmitted intensity to a maximum or the reflected intensity to a minimum.

As shown in Fig. 2, the two beams are obtained by dividing the original laser beam with a beamsplitter.[5] The original laser frequency f_0 is Bragg shifted to $f_0 + f_1$ and to $f_0 + f_2$ through diffraction from acoustic waves of frequency f_1 and f_2 generated in the two acousto-optic modulators. Feedback signals to a piezoelectric transducer (PZT) mounted on one of the cavity mirrors lock the CW resonant frequency of the cavity to

$f_0 + f_1$ by changing the length of the cavity until a maximum is received by the photodetector. A second loop locks $f_0 + f_2$ to the CCW resonant frequency of the cavity by adjusting f_2 until a maximum is received by the detector. The frequency difference between f_1 and f_2 allows the calculation of Δf via Eq. (2).

Unfortunately, this design is inappropriate for high-sensitivity applications. As discussed before, to increase the sensitivity the cavity linewidth must be narrowed. Industry is able to manufacture cavities whose linewidths are narrower than commercially available frequency-stabilized lasers. This presents a problem with the design because, while in resonance, much of the laser's energy is outside the bandpass of the cavity, producing a poor signal-to-noise ratio and poor operation of the control loops.[7]

Adding to this problem is that the narrow line width cavity exhibits a significant time constant.[10] Consider, again, Fig. 1 where the incident light is in resonance with the cavity. A relative phase shift between the incident beam and the running wave stored in the cavity will result in an immediate increase in the reflected intensity. However, the decrease in the transmitted intensity is delayed because of the large amount of energy stored within the cavity I_c, compared to the amount transmitted through the input mirror. Therefore, a filtering effect is observed with a time constant on the order of the cavity lifetime. The controller is then prevented from compensating for any high-frequency phase fluctuations. For narrow linewidth cavities, this time constant is on the order of a millisecond, which significantly limits the bandwidth available if the transmitted beam is used to drive the control electronics. The concept of using the reflected beam to maintain resonance solves this difficulty and has been demonstrated elsewhere.[7,11]

The design presented here takes into account these two problems by locking the laser's frequency to a cavity resonance, thereby narrowing the laser's linewidth to less than the cavity linewidth and using information derived from the reflected beam to drive the control electronics. The bandwidth of the current apparatus is still limited by the cavity ring-down time (i.e., a photon's lifetime inside the cavity), since the error signal is generated by dithering the cavity path length. The goal is to demonstrate a completely passive cavity concept in which the error signal is generated by electro-optically modulating the phase of the incident beam. This is especially important for scaling to large, high-finesse ring cavities having long cavity photon lifetimes (narrow linewidths) and scale factor stability considerations that dictate a truly passive cavity approach.

Laser Stabilization

For this experiment, frequency stabilization of a 1 mW, single-mode, He-Ne laser is performed by controlling the optical path length of the laser cavity through the addition of two control circuits to the laser gain tube. A schematic diagram of these circuits is shown in Fig. 3. One circuit controls the discharge current and, hence, the index of refraction within the gain tube. The other circuit controls the physical distance between the two laser mirrors. Driven by appropriate signals, these two circuits control the resonant condition of the laser cavity that, in turn, allows for the control of the laser's output frequency.

The discharge current control circuit provides a high-speed (potential bandwidth of about 50 KHz) control of the laser's frequency such that the laser's frequency changes by approximately 100 KHz per volt applied. Unfortunately, this circuit does not provide the dynamic range required to compensate for the large (> 1 MHz) fluctuations in the uncontrolled laser frequency. To supplement this servo, a lower-frequency control loop (bandwidth of about 20 Hz) is added. A section of heater tape wrapped around the gain tube allows for thermal expansion of the tube to change the laser's path length. By applying voltage to the heater, the physical distance between the laser mirrors is adjusted such that the laser frequency is changed by approximately 100 MHz per volt applied to the heater. Together these circuits provide the quick response and sufficient dynamic range to compensate for most fluctuations of the laser's frequency.

As shown in Fig. 4, tests to observe the performance of the laser frequency stabilizer are set up so that the optics are consistent with those required for the PRRG. The polarization of the laser light is aligned to the S-polarization mode of the resonant cavity by sending the beam through a half-wave plate ($\lambda/2$). Two cylindrical lenses then focus the laser beam and match it to the fundamental transverse electromagnetic ($TEM_{0,0}$) mode of the cavity.[11] This mode-matching technique allows for the greatest transfer of laser energy into the cavity.

Before the beam enters the resonant cavity, an acousto-optic modulator (A/O) shifts the frequency of the beam f_0 by a constant frequency f_1 (typically 40 MHz). In addition, the A/O reduces optical feedback into the laser gain tube, which can destabilize the laser output frequency. Photodetectors are positioned so that the beam transmitted through the resonant

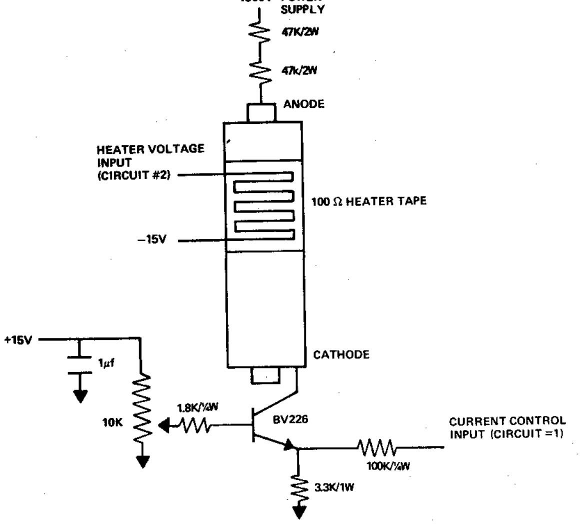

Fig. 3 Laser frequency control circuits.

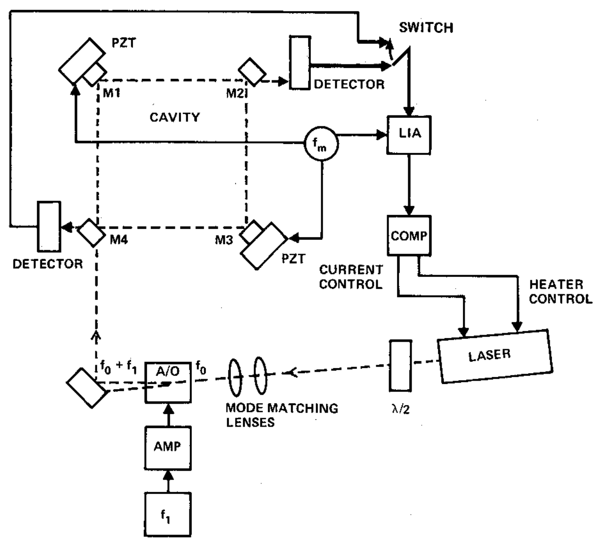

Fig. 4 Laser stabilization setup.

cavity as well as the beam reflected off the input mirror M4 can be monitored. In this way, the laser frequency can be locked to either the resonant peak of the transmitted beam or the resonant valley of the reflected beam so that the performance characteristics of locking to either beam can be studied.

The feedback control loop is driven by a 30 KHz modulation signal f_m applied to the two PZT's mounted on each of the two spherical cavity mirrors. This probing signal allows for the determination of an error signal that indicates the degree to which the laser is in resonance with the cavity. The reflected (transmitted) intensity signal derived from one of the photodetectors is input into a lock-in amplifier (LIA) where it is notch filtered at $2f_m$ to eliminate rectification of the modulation signal and then demodulated. This signal is then fed into a proportional-plus-integral (PI) controller and then applied to the laser control circuits.

The PI controller is shown in Fig. 5. The demodulated signal from the LIA is integrated, amplified, and then sent to the discharge current control circuit. In addition, this signal is integrated again before applying it to the heater control circuit. The controller gains were determined experimentally using "observed stability" and "perturbation response" criteria.

After numerous iterations, a combination of gains that yielded a stable response was found. The proportional and integral gains were subsequently tuned slightly to improve stability and response to input perturbations. Sinusoidal perturbation signals were summed with the PZT modulation signal. Tuning was accomplished by observing the frequency spectrum of the error signal on a Fourier analyzer. Ideally, only a frequency component at twice the modulation frequency should have been observed. Gains that minimized other frequency components while maximizing the $2f_m$ component were selected.

PRRG Experiment

The laser stabilization loop of Fig. 4 is modified to operate as a PRRG as shown in Fig. 6. Following previous designs,[5-7] a secondary loop is added which adjusts the frequency f_2 of the A/O in the clockwise beam path so that f_0+f_2 matches the clockwise resonance frequency of the cavity. The signals for this loop originate at the outputs of the two photodetectors monitoring the reflected intensity from the two input mirrors. The two intensities are differenced at the LIA to reduce residual noise common to both beams. This difference signal is subsequently notch filtered at $2f_m$ and demodulated. The output of the LIA is then compensated by a PI controller (see Fig. 7) whose output is then used to drive a voltage-controlled oscillator (VCO) to produce f_2. As before, the gains for the controller were determined experimentally using "observed stability" and "perturbation response" criteria.

To maintain beam alignment, stable optical mounts were used and all experiments were conducted in a temperature-controlled environment. To reduce vibration effects, the PRRG assembly was mounted on a rate table that was, in turn, mounted atop one of the isolation piers of the seismically stable platform in the Seiler Laboratory.

Following this preparation, the task of measuring rotation rates was addressed. The PRRG was subjected to the vertical component of Earth rate at 39 deg latitude, while a frequency counter measured the difference frequency for 1 s sample times. These data were recorded directly onto a floppy disk for post-test processing. A straight line was fit to the Δf data and the standard deviation of the residuals from the fit line were computed. The slope of this line was used to determine the bias drift and the standard deviation of residuals from the line defined the random error.

From these data, the rate bias, the long term bias drift, and the short-term random error were determined by comparing the data to the expected Δf (11.61 Hz) corresponding to the inertial rotation rate. To determine random error as a function of sample times other than 1 s, the Δf data was averaged by computer to form 10, 50, 100, 500, and 1000 second samples.

Results

Table 1 summarizes the results from the five 4 h tests conducted on the PRRG. The random error performance as a

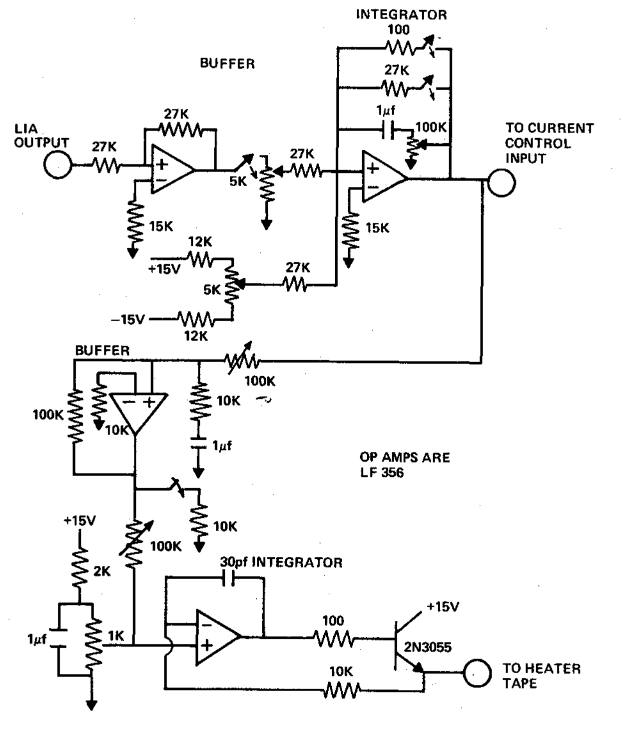

Fig. 5 Laser frequency control compensator.

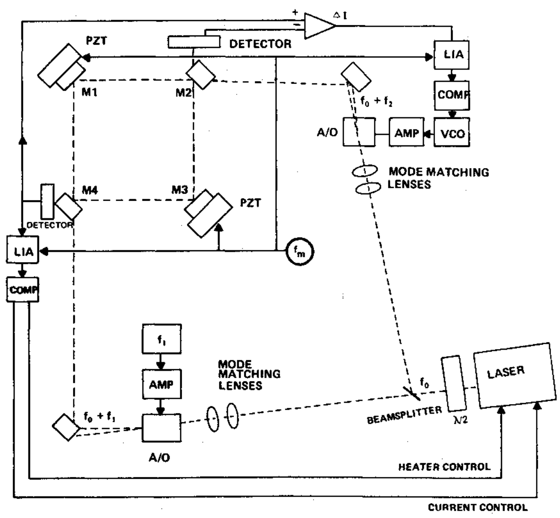

Fig. 6 PRRG setup.

Table 1 Test results

Test	Average	Standard Deviation
Bias, ERU	0.99	0.085
Bias drift, ERU/h	0.103	0.0099
Random error, ERU $\tau = 10$ s	0.0078	0.0017

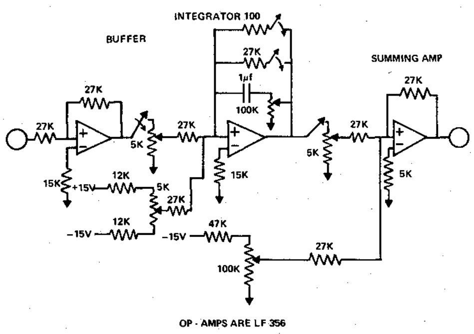

Fig. 7 Secondary loop compensator.

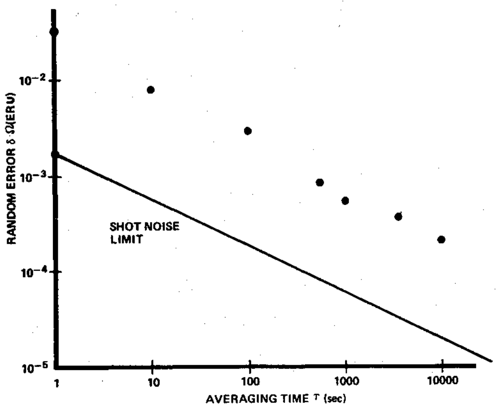

Fig. 8 Random error vs averaging time.

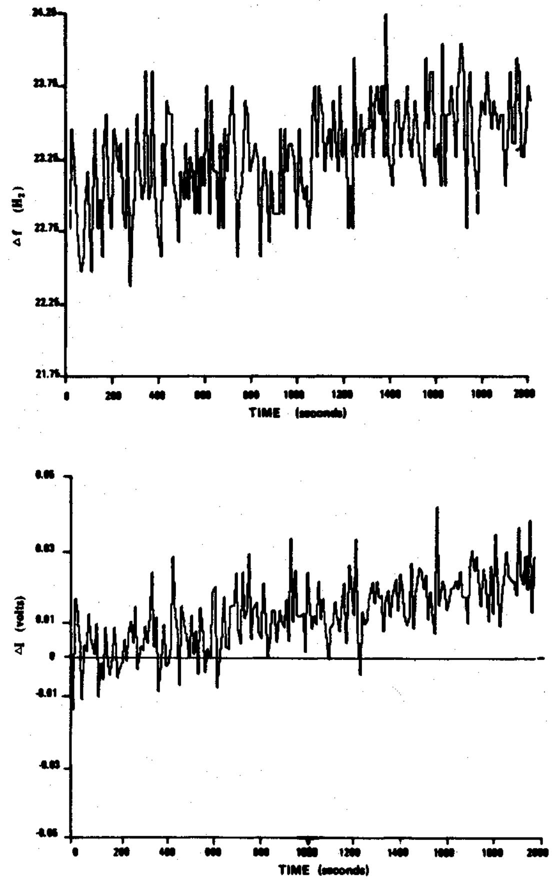

Fig. 9 Correlated ΔI and Δf drifts.

function of averaging time is presented in Fig. 8. Bias drift is removed from this data by subtracting the value of the drift at each data point as determined by a least-squares linear fit to the Δf data. The solid line represents the shot noise limitation for this instrument as a function of averaging time as derived from Eq. (3).

The primary cause of the long-term bias drift was found to be due to a drift in the signal corresponding to the difference between the two reflected intensities used to drive the secondary loop (see Fig. 6). Although the reflected intensities were equalized prior to the tests, the intensity difference (ΔI) drifted during the test. Previous studies have shown the effect of the changing ΔI and support this hypothesis.[12] As shown in Fig. 9, the bias drift was highly correlated to the ΔI drift.

In achieving the thermally stable environment in the laboratory, air currents and pressure changes caused by the environmental control unit were encountered. This induced a considerable amount of phase noise in the reflected beam, which led to an increase in noise at the detector. Because the noise was outside the bandwidth of the controller, the electronics could not compensate for it. We felt that the combination of the high-frequency noise in the laser beam (as well as other sources) and the limited bandwidth of the control system were the primary reasons for the PRRG performance being above the shot noise limit.

Research on improving the performance of this approach is continuing. Current initiatives involve incorporating several improvements to reduce the random error and long-term bias drift, as well as improve controller bandwidth. For example, the bias drift could be diminished by real-time control of the intensity of each of the beams through the amplitude of the acoustic wave within the acousto-optic modulator. The controller bandwidth could be increased by electro-optic modulation of the beam instead of the cavity path length modulation. In addition, the problem with phase noise due to air currents may be reduced by isolating the apparatus by covering it. Finally, recent work by others[13] has shown a more efficient laser stabilization controller that could be adapted for the configuration.

Conclusions and Recommendations

Even though the performance of this PRRG is about one order of magnitude above the shot noise limit, the results from this experiment are encouraging for the development of larger PRRG's. Comparing this performance to one constructed earlier at the Seiler Laboratory[12] that used the traditional cavity locking technique shows considerable improvement in both random error (0.0078 vs 0.018 ERU) and long-term bias drift (0.103 vs 2 ERU/h). This is an appropriate comparison as the optical cavity as well as much of the electronics were the same for both experiments. Extrapolating this comparative performance to a proposed 60 m^2 PRRG indicates sensitivities in the 10^{-7} ERU range are attainable.

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