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Passive ring resonator laser gyroscope*

S. Ezekiel and S. R. Balsamo†

Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

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A new method of measuring inertial rotation is presented. It is based on the use of a passive ring resonator as the rotation sensing element and an external laser for measuring the difference between the clockwise and counterclockwise lengths of the resonator. Preliminary performance data is included.

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The use of lasers in the measurement of inertial rotation has been receiving considerable attention for more than a decade. The major effort has been in the development of a ring laser which supports two counterpropagating oscillators that share a common cavity as well as a common amplifier.[1] In the presence of rotation with respect to inertial space perpendicular to the plane of the cavity, the degeneracy in the frequencies of the two oscillators is removed. This is caused by the fact that the optical length of the clockwise (CW) and counterclockwise (CCW) paths around the ring are no longer equal, as demonstrated by Sagnac.[2]

In this paper we report a new method of measuring inertial rotation, also based on the Sagnac effect, which promises to be free from the major problems normally encountered in the ring laser gyroscope, such as the lock-in phenomenon at low rotation rates, bias drift, and scale factor variation which are all attributable to the presence of the gain medium within the ring cavity.[3]

The new concept is based on the use of a passive ring Fabry-Perot interferometer as the rotation sensing element and the use of an external laser to measure any difference between the CW and CCW lengths of the cavity caused by inertial rotation. Because the reference cavity is passive, all the problems normally associated with the gain medium in the conventional ring laser gyroscope are eliminated.

Several schemes of implementing such a concept are possible but only two are discussed here and are illustrated in Fig. 1. One scheme, shown in Fig. 1(a) employs two independently controlled laser frequencies to measure the CW and CCW resonance frequencies of the passive ring. To avoid the problem of uncorrelated laser jitter when two separate lasers are used, we have chosen to derive the two independently controlled laser frequencies from one laser by the use of two frequency shifters such as acousto-optic devices. As shown in Fig. 1(a) the frequency of an external laser f_0 is shifted to f_0+f_1 by an acousto-optic crystal driven at f_1 and to f_0+f_2 by another crystal driven at f_2. As long as f_1 and f_2 are derived from low jitter rf oscillators, the frequency jitter in f_0+f_1 and in f_0+f_2 are identical. The measurement of cavity path-length difference may be accomplished by locking the CW resonance frequency of the cavity to f_0+f_1 by means of an electronic feedback loop using a piezoelectric length transducer,[4] as shown in Fig. 1(a). A second feedback loop is used to lock f_0+f_2 to the CCW resonance frequency of the cavity by adjusting f_2. In this way, the difference between f_1 and f_2 is directly proportional to inertial rotation.

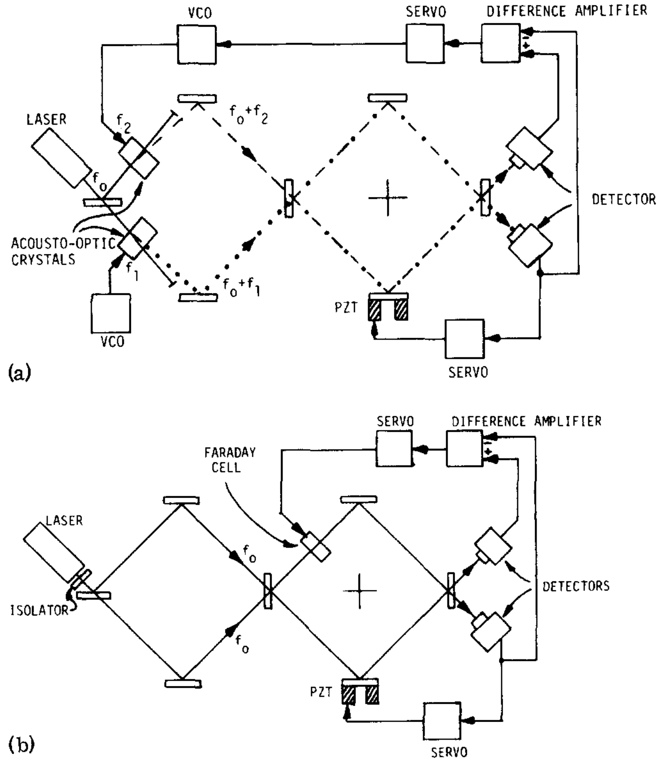

FIG. 1. Schematic diagram of two configurations for a passive ring resonator laser gyroscope. (a) using acousto-optic frequency shifters and (b) using an intracavity Faraday cell.

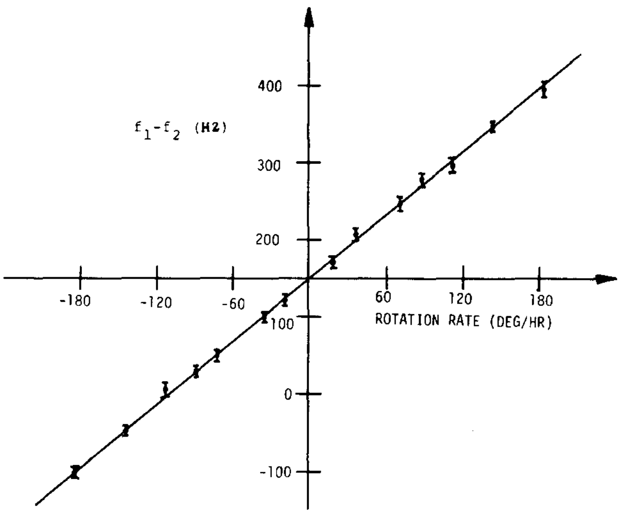

FIG. 2. Measured frequency difference ($f_1 - f_2$) as a function of rotation rate Ω.

Another scheme, shown in Fig. 1(b) employs only one laser frequency and a means of nulling out any difference between CW and CCW path length caused by inertial rotation by using, for example, a Faraday cell within the cavity. As shown in Fig. 1(b), the CW resonance frequency of the cavity is locked to the laser frequency f_0. In the presence of inertial rotation, the CCW resonance frequency will no longer be at f_0 and this frequency difference is then used as an error signal in a feedback loop driving the Faraday cell to bring the CCW resonance frequency back to f_0. In this way, the current needed to drive the Faraday cell is directly proportional to inertial rotation.

In both schemes, the difference between CW and CCW resonance frequencies of the cavity Δf caused by a rotation Ω normal to the plane of the cavity is given by the Sagnac effect[5] as

$$\Delta f = (4A/\lambda P)\Omega,$$

where A is the area enclosed by the cavity, P is the perimeter, and λ is the wavelength of the light. The precision with which Δf can be measured depends on the Q of the cavity, in other words on the instrumental linewidth of the cavity Δf_c and on the signal-to-noise ratio in the measurement. Assuming shot-noise-limited detection, it should be possible to measure a rotation rate with an uncertainty $\delta\Omega$ given by

$$\delta\Omega \approx 10^5 \lambda P \Delta f_c / 4A(N\eta\tau)^{1/2} \quad \text{deg/h},$$

where N is the number of photons per second transmitted at the peak of the cavity resonance, η is the photodetector quantum efficiency, and τ is the integration time. For example, for $\lambda = 6328$ Å, $P = 40$ cm, $A = 100$ cm^2, $\Delta f_c = 1$ MHz, $N = 2\times 10^{14}$ photons/sec, $\eta = 0.5$, and $\tau = 1$ sec, we get $\delta\Omega \approx 0.05$ deg/h.

We have performed preliminary experiments using the configuration in Fig. 1(a). We used a square cavity made of solid aluminum, measuring 17.5 cm on a side. The corners are terminated with two flat and two curved mirrors and one of the cavity mirrors is mounted on a piezoelectric transducer. The output from a linearly polarized 1-mW single-frequency He-Ne laser is split into two beams, each of which is upshifted by an acousto-optic crystal and then coupled into the cavity. The acousto-optic crystals are driven by two stable and independent voltage-controlled oscillators operating around 40 MHz. In our setup, the CW cavity resonance is locked to $f_0 + f_1$ and f_2 is adjusted by a second feedback loop so that $f_0 + f_2$ is held at the resonance frequency of the CCW cavity. To eliminate the effect of cavity and laser jitter on the measurement of f_2, the outputs of the two detectors are subtracted so that only their difference is fed as an error signal into the second feedback loop. In this way, the second loop is only sensitive to a nonreciprocal cavity length change such as that caused by inertial rotation.

The entire setup was placed on a motor driven turntable. Figure 2 is a plot of $f_1 - f_2$ as a function of table rotation rate Ω. The linear relationship between $f_1 - f_2$ and Ω indicates the absence of lock-in between the counterpropagating frequencies. This is as expected since any coupling between the CW and CCW frequencies, for example, by backscattering at mirror surfaces, causes frequency pulling but not lock-in. In our setup, it is easy to measure any coupling between the beams by simply blocking one beam and observing the backscattered light transmitted in the opposite direction. We measured such backscattering and found it negligible.

The bias drift was also investigated. Figure 3 shows $f_1 - f_2$ as a function of time while the turntable was stationary. No noticeable drift was detected in a time interval of 1 h. The rms fluctuation in the output for $\tau = 10$ sec corresponds to about 10 deg/h and this is large compared with anticipated values for the present setup. Several sources of noise are being investigated. A more detailed paper on our experiments will be submitted for publication shortly.[6]

The passive ring resonator methods of measuring inertial rotation discussed in this paper are of course not free of potential problems. The stability of the cavity as well as the stability of the alignment of the

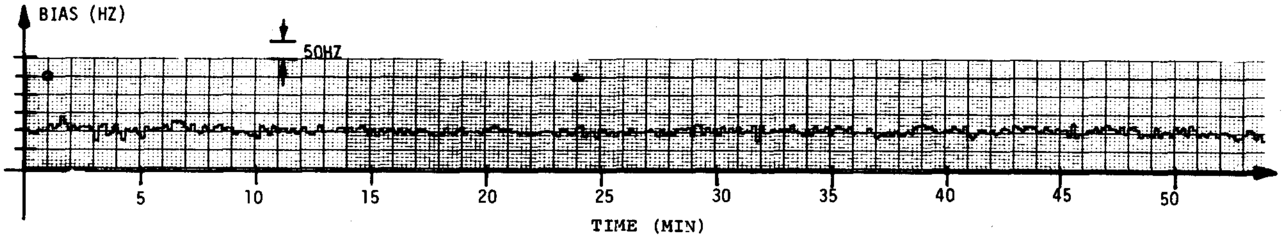

FIG. 3. Measured frequency difference ($f_1 - f_2$) as a function of time (turntable stationary); integration time = 10 sec. An $f_1 - f_2$ of 50 Hz is equivalent to a rotation rate of 37 deg/h.

external beams are crucial. Considerable care must be exercised to ensure that both cavity directions are excited in the same manner. Errors can also be caused by changes in the polarization of the light, changes in intensity, as well as nonideal performance of the electronic feedback loops.[6] Furthermore, to achieve a constant scale factor $(4A/\lambda P)$ the laser frequency must be long-term stabilized, for example, to the center of the gain curve or Lamb dip. The serious problem of the reflected beams reentering the laser is prevented in the configuration of Fig. 1(a) by the presence of the acousto-optic crystals and in Fig. 1(b) by an optical isolator, for example, an acousto-optic crystal.

The concepts outlined in Fig. 1 may be applied to the construction of large-area ring cavities for applications in geophysics such as earth wobble measurements or in testing of precision turntables or gyroscopes. If a ring cavity, 2 m on a side, is used with a 3-W single-frequency argon ion laser, it should be possible to measure earth rotation with an uncertainty of 5 parts in 10^9 in an integration time of 1000 sec.

An exciting possibility is to replace the mirror-terminated cavity with a closed fiberoptic ring.[7] Low-loss single-mode fibers are available so that the only major problem remaining is the design of efficient means of coupling light into and out of the fiber ring. Such possibilities are under investigation in our laboratory including the use of semiconductor and Nd-YAG lasers.

Finally, the highly precise techniques for the measurement of small path length or phase shift in a ring cavity described in this paper are clearly applicable in spectroscopy. For example, if a gas cell is placed within the cavity and an intense beam from a tunable laser is propagated along one direction and the same but much weaker beam is propagated in the opposite direction, it would then be possible to perform saturated dispersion spectroscopy[8] of the gas in the cell. The sensitivity of such a method would be extremely high coupled with the high-resolution capability made possible by the saturation effect. Another spectroscopic application that is being pursued in our laboratory is the use of the concepts in Fig. 1 to detect parity nonconservation due to weak neutral currents by measuring the phase difference between right circularly polarized and left circularly polarized light propagating in opposite directions in a cell (or in an atomic beam) of cesium.[9]

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Seventh harmonic conversion of mode-locked laser pulses to 38.0 nm

J. Reintjes, C. Y. She,[*] R. C. Eckardt, N. E. Karangelen, R. A. Andrews, and R. C. Elton

Naval Research Laboratory, Washington, D. C. 20375

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Seventh harmonic generation in helium is used to produce coherent light at 38 mm from laser pulses at 266.1 nm. The variation of both the fifth and seventh harmonic signals with helium pressure is described.

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Frequency upconversion using nonlinear optical interactions have proven to be an important source of coherent radiation in the vacuum ultraviolet region of the spectrum.[1,2] We have previously reported[3] the generation of coherent light at 53.2 nm through fifth harmonic conversion of laser pulses at 266.1 nm. In this paper we describe the first observation of seventh harmonic conversion of laser radiation and the generation of coherent light at 38 nm in helium; this is the shortest-wavelength coherent radiation which has yet been reported. In addition to reporting this new wavelength radiation we present measurements of both the fifth and seventh harmonic signals as a function of helium pressure. These results show that conversion efficiency varies as N^2 for low pressures (N = helium density), and shows a weaker dependence for pressures above 10 Torr. Possible sources of this limitation on conversion are discussed.

A partial energy level diagram of helium is shown in Fig. 1 where the levels involved in the harmonic generation processes are indicated. The fifth harmonic