Development of Compact Resonator Fiber Optic Gyroscopes

Glen A. Sanders, Lee K. Strandjord, Jianfeng Wu, Wes Williams, Marc Smiciklas, Mary Salit, Chellappan Narayanan, and Tiequn Qiu
Honeywell International, USA

Abstract—In this paper we report progress toward a compact resonator fiber optic gyroscope (RFOG) design for commercial navigation applications. Specifically, we report the first use of silicon optical bench (SIOB) technology within the gyro to miniaturize optical component size. A low loss SIOB is used for optical resonator loop closure and a promising initial finesse of 35 is observed. The gyro angle random walk is 0.0029 deg./rt.-hr., and first results show a bias stability of better than 0.1 deg./hr for a sensing coil diameter of two inches. These results represent an encouraging step toward the realization of a practical navigation-grade RFOG for civil navigation usage.

Keywords—resonator fiber optic gyro; silicon optical bench; fiber optic resonators; optical gyroscopes

I. INTRODUCTION

The resonator fiber optic gyro (RFOG) is being pursued because of its theoretical potential to meet navigation grade performance in a smaller size and lower cost than ring laser gyros (RLGs) and interferometric fiber optic gyros (IFOGs) [1]. This is due to the fact that the RFOG combines sensitivity-increasing signal to noise attributes of recirculating the light in a resonant cavity like an RLG, in addition to the ability to wind longer path length multi-turn coils like an IFOG, using optical fiber. While the promise of the RFOG approach has focused on feasibility realizing required performance using a relatively short fiber sensing coil, the other optics must be miniaturized and cost-reduced to take advantage of the benefits of the resonant sensing coil architecture. This paper reports recent progress in resonator fiber optic gyroscope (RFOG) development towards realization of a next generation compact device for commercial navigation applications by incorporation of silicon optical bench technology to miniaturize resonator and input optics. Progress of all-fiber implementations of similar to the arrangement reported here, have been recently reported recently [2, 3]; however, they are less likely to meet the small-size and low-cost demands of the navigation market. A new design realized with a relatively small fiber-optic resonator (of 2-inch diameter) and optics on a tiny silicon optical bench (SIOB) is presented for the first time, along with initial test data. The incorporation of the SIOB technology represents an important step forward in the miniaturization of the RFOG technology. In addition, the SIOB technology promises to be compatible with high volume, low-cost manufacturing techniques used for silicon processing, and automated assembly techniques.

II. EXPERIMENTAL ARRANGEMENT

The RFOG configuration is shown schematically in Fig. 1. The RFOG concept, based originally on a passive cavity gyro approach [4], utilizes the Sagnac Effect for measuring rotation rate due via the resonance frequency shift between clockwise (cw) and counterclockwise (ccw) resonances in a fiber ring resonator. The resonance frequency shift is proportional to the inertial rotation rate experienced along the sensitive axis of the fiber optic resonator. In the RFOG arrangement we report here, the sensing coil consists of a fiber optic coil wound on a two inch diameter mandrel, plus coupling optics mounted on a tiny silicon chip (see Fig.1). Light propagates in cw and ccw directions around the multi-turn fiber optic coil consisting of 100m of polarization maintaining fiber. The ends of the fiber coil are placed in a v-groove etched in a silicon substrate forming the SIOB. By laying fibers in opposite ends of a v-groove with ball lenses in between, light is aligned and focused from one end of the loop fiber to the other. In the region between the ball lenses, light is collimated so that tiny beam-splitters can couple the light into and out of the resonator. In between optics on the SIOB, light travels through free space. The SIOB plays a critical role in closing the resonator loop by connecting two ends of the coil, as well as providing an input light path into the resonator, and out of the resonator. The input paths also incorporate circulators on the chip to attenuate feedback to the lasers.

Fig. 1. Resonator fiber optic gyro using miniaturized optics on silicon optical bench
An example of the resonator loop closure region on an SIOB test device is shown photographically in Fig. 2. In the photograph, the v-groove for the resonator runs from upper left to the middle right side of the photo. The input/output beam-splitters are shown in between the two ball lenses used to collimate the light through the beams-splitters and focus the light into fibers. In the case of this test device, light was to be coupled into the resonator path by means of two fibers laying in parallel input v-grooves (shown in Fig. 2) followed by ball lenses.

To form the gyro of Fig.1, the laser light consists of two slave laser (SL) diodes and one master laser (ML) diode. Light from the master laser is modulated in a phase modulator (PM3) before being directed to the SIOB, which directs it to propagate in the cw direction of the resonator. A portion of the master laser light is detected in reflection from the resonator on the rightmost detector and demodulated at the frequency imparted to PM3. The demodulated signal serves as an error signal for a servo loop that tightly locks the master laser to the resonator using the well-known Pound-Drever-Hall (PDH) stabilization technique. A portion of the light emitted from the ML is combined with the output of each of the slave lasers to form a beat note. The respective detected beat notes from the master laser and SL1 and SL2 are used to phase lock each of them to the ML with a tunable offset frequency using an Optical Phase Lock Loop (OPLL). Light from SL1 propagates in the cw direction of the resonator, while that of SL2 propagates in the ccw direction.

In order to measure the rotation rate, the some of the cw wave from the resonator is coupled out via a resonator input/output beam-splitter, passed through a circulator located on the SIOB (middle features on SIOB) and coupled to a transmission port detector. The output of this detector is then demodulated at the phase modulation frequency applied to PM1 to form a discriminant for the CW Resonance Tracking servo, which adjusts the frequency of SL1, via the OPLL, to a resonance condition in the cw direction. Likewise, the frequency of SL2 is adjusted to resonance in the ccw direction. Each of the input light waves is passed through an intensity modulator (IM) which controls the power input to the resonator.

There are two countermeasures in this arrangement used to minimize errors from Rayleigh backscatter. First, the two slave lasers are locked to two different longitudinal resonances of the resonator. This provides a large frequency difference between the two waves (roughly 2 MHz for this resonator), which makes interference between signal light and backscattered light occur at a high beat frequency, which can be filtered from the rotation signal [2,3]. In addition, the modulation frequencies applied to the cw and ccw input light in PM1 and PM2 are selected to be different. This is done to separate signal light from the intensity (non-interference term) of back-reflected light; thus, avoiding errors that would be caused primarily by Rayleigh backscatter [5].

\[
\text{Spectral Density of Rate (deg/hr)^2/Hz)}
\]

\[
\text{Spectral Density of Rate (deg/hr)^2/Hz)}
\]

\[
\text{Spectral Density of Rate (deg/hr)^2/Hz)}
\]
of 0.00293 deg/rt-hr at 10 Hz for a 2-inch diameter coil. The results are consistent with civil navigation grade performance.

![Resonator Finesse vs. Temperature](image)

Fig. 5. Finesse as a function of temperature (in degrees Celsius) of a resonator using a silicon optical bench to close the resonator loop.

### III. RESULTS AND DISCUSSION

Several key questions were addressed for the first time in this work. Of specific importance in this advanced RFOG design is the attainment of sufficiently high resonator finesse with an SIOB in the resonator loop, to achieve desirable angle random walk (ARW) performance. A scan of the resonances in one direction of the resonator is shown in Fig. 3. As is shown, a finesse of 35 in a 2-inch diameter coil has been obtained for a 100 meter length has been realized. This result allowed enabled a navigation grade ARW performance of about 0.0029 deg./rt.-hr. This is depicted in Fig. 4, where the power spectral density (PSD) of the gyro output is plotted. The white noise is given by the region on the right hand side (at 10 Hz) where the noise is flat, and no longer influenced by 1/f noise.

Several Also, of critical importance is the assessment of the effect on bias performance of adding the SIOB in the resonator. First results show bias stability around 0.1 deg./hr. over a 1 hour time duration. These very encouraging early results are amongst the best reported results for RFOGs, even though they are the first report of introducing an SIOB into the loop. Greater study of bias stability for this device is anticipated.

Finally, we also report our first results of testing the temperature stability of an SIOB test device. This is particularly significant because any misalignments and loss variation in the fiber-to-fiber coupling within the resonator loop can adversely affect the finesse. As a first trial, we subjected an SIOB based resonator device with a finesse of around 20 to a variation in temperature, as is shown in Fig. 5. The SIOB temperature was varied over a non-condensing temperature range of 20 degree C to 85 degree C (the unit was not packaged or sealed). As depicted in Fig. 5, its finesse demonstrates remarkable stability showing negligible change over temperature.

### IV. CONCLUSION

The results reported here demonstrate an encouraging first step toward the realization of a low loss, miniature silicon optical bench platform for RFOG applications. This is a significant step in the development of a compact RFOG along with the best reported RFOG ARW to our knowledge. The obtained ARW of 0.0029 deg/rt.hr is consistent with many navigation applications in civil aviation.

### REFERENCES
