Integrated Sagnac Optical Gyroscope Sensor Using Ultra-Low Loss High Aspect Ratio Silicon Nitride Waveguide Coil

Sarat Gundavarapu*, Michael Belt, Taran Huffman, Minh A. Tran, Tin Komljenovic, John E. Bowers, and Daniel J. Blumenthal; Department of Electrical and Computer Engineering, University of California, Santa Barbara, CA 93106, U.S.A

ABSTRACT

We demonstrate operation of an interferometric optical gyroscope that uses an on-chip 3m ultra-low-loss silicon nitride waveguide coil. The measured minimum waveguide loss of the waveguide coil fabricated using lithographic die stitching was 0.78 dB/m. The angle random walk and bias instability of the gyroscope were characterized to be 8.52 deg/hr$^{1/2}$ and 58.7 deg/hr respectively.

Keywords: Inertial motion units; Gyroscopes; Lithographic die stitching; Ultra low loss Si_3N_4 waveguide delay coils;

1. INTRODUCTION

Gyroscopes are used in inertial motion units (IMU)/ inertial navigation systems (INS) to determine the position and orientation of an object based on its inertial reference frame. Over the past few decades, advances in gyroscope technologies[1] have been instrumental in the realization of high precision IMUs. MEMS gyroscopes, laser gyroscopes, and interferometric fiber optic gyroscopes are among the commercially mature and available technologies that are widely used in navigation, tactical, and industrial applications. Considerable research has been invested in the characterization and miniaturization of interferometric optical gyroscopes (IOG) while maintaining their high sensitivity and performance specifications. The performance of an IOG scales with length, area, and polarization extinction of coils. However, it has been challenging to realize an on-chip waveguide coil based IOG with desired performance due to high waveguide loss, available chip real estate (maximum coil length), and the lack of a well-established high performance integration platform. The Si_3N_4 based ultra-low loss waveguide (ULLW) platform provides a solution to enable long, on-chip millimeter diameter scale waveguide coils with losses less than 0.1 dB/m[2,3]. In addition to the low loss of the ULLW platform, the high polarization dependent loss (> 75 dB) of ULLW coils[4] plays an important role in minimizing parasitic effects due to polarization drift and drift in polarization coupling between bulk optical components, resulting in improved performance for parameters like angular random walk (ARW). Chip scale integration of the IOG can improve the manufacturability of IOGs in general, while at the same time significantly reducing the size, weight, and cost. We reported the preliminary results of a Sagnac sensor realized using an ultra-low loss high aspect ratio Si_3N_4/SiO_2 planar waveguide coil in our previous work[6].

In this paper, we report the first rotation measurements performed by a gyroscope that uses a 3 m integrated Si_3N_4 waveguide delay coil. The angle random walk (ARW) and bias instability (BIS) were evaluated using the standard Allan variance method.

2. INTEGRATED GYROSCOPE

2.1 Integrated Gyro Design

The optimal length of the ULLW Si_3N_4 coil to be used in an integrated optical gyroscope to achieve best noise performance was estimated to be 3-10 m[7,10]. The chosen coil geometry for this work was a 3 m Archimedian spiral with outer radius of 20 mm, waveguide spacing of 50 μm, and inner radius of 18.75 mm, with a total of 50 waveguide crossings per round trip. The ARW of the gyroscope using this coil was calculated[7] to be 1.15 deg/hr$^{1/2}$. The waveguide coil was fabricated using lithographic die stitching and was packaged to perform rotation measurements using the setup shown in Figure 1. Details of fabrication, coil packaging, gyroscope characterization will be presented in the subsequent sections.

*saratchandra@ece.ucsb.edu

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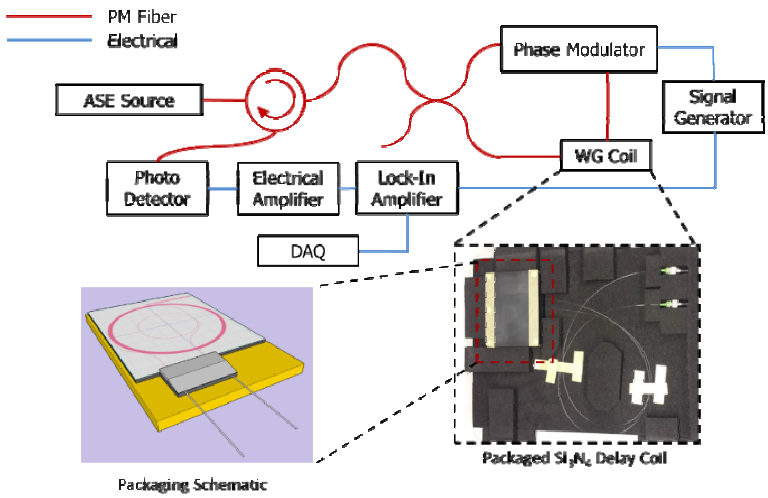
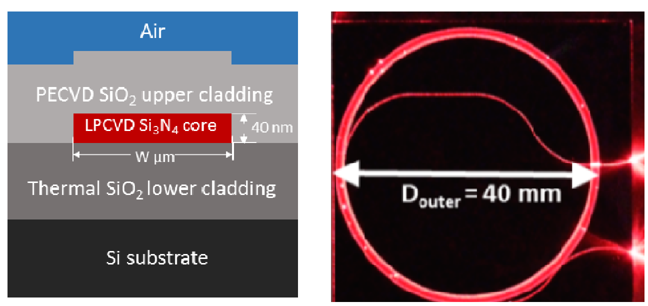


Figure 1. Integrated waveguide coil gyroscope measurement setup

2.2 Waveguide Coil Design and Fabrication

The use of thinner waveguide cores improves propagation and crossing losses (with sidewall roughness being the dominant contribution to both of these characteristics) but places a limitation on the waveguide bend radius[2]. Here we choose to use a 40 nm thick Si_3N_4 core to give us minimal possible loss values, which constrains our bend radius to 11 mm[7]. The lithographic stepper system used in our fabrication process has a maximum die size of 21x25 mm that limited the bend radius to 10 mm within a single field. Ultra-low loss stitching[7] of 4 different DUV fields was used to realize the designed coil geometry (Figure 2(a)) by increasing the achievable coil radius to 20 mm.



(a) (b)

Figure 2. (a) Cross section schematic of waveguide design (b) Top view of 3 m waveguide coil illuminated using red laser

The lowest-case (waveguide loss + stitching loss) and crossing loss of the 3 m waveguide coil (Figure 2(b)) fabricated using this lithographic side sitching were measured to be 0.78 dB/m and 0.0156 dB/crossing respectively.

2.3 Packaged Coil

In order to assess the performance of waveguide coil as the sensing element in a gyroscope, it has to be packaged and mounted on a rotation stage for measurements. Polarization maintaining (PM) fiber V-groove arrays (VGA) were used to edge couple in to the waveguide coil facets as shown in the packaging schematic in Figure 1. The packaging loss per facet after epoxy and UV cure was found to be in excess of 6 dB resulting in a total insertion loss of 16.2 dB with a broadband source. Coupling losses of (0.4 ± 0.2) dB per transition between silicon and ULLW layers have been demonstrated[5], which would provide a solution to get rid of high fiber to such high fiber to waveguide coupling loss through chip scale integration of all IOG components.

3. GYROSCOPE CHARACTERIZATION AND PERFORMANCE MEASUREMENTS

3.1 Proper Frequency

In order to achieve maximum sensitivity and minimize the effect of several noise factors, it is important to operate the gyroscope with a phase modulator biased at proper (Eigen) frequency[8] of the coil, especially for shorter coil lengths. The proper frequency was determined by performing a ramp frequency sweep (as described in our previous paper[6]) to be 21.02 MHz (Figure 3). The measured value is in accordance with the expected value of proper frequency based on actual length of the waveguide coil and the fiber pig tails (total length ~ 5 m).

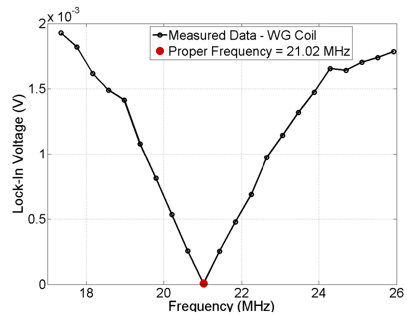
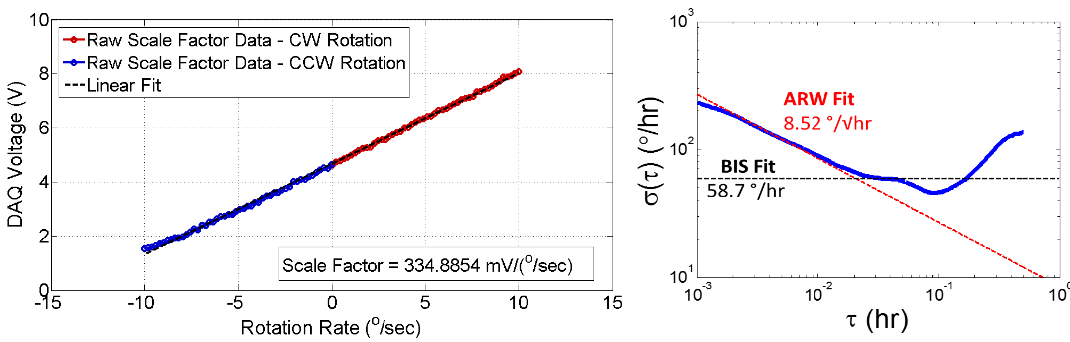


Figure 3. Proper frequency measurement

3.2 Rotation Signal Measurement and Noise Characterization

A high precision rotation stage, Ideal Aerosmith 1270VS was used to calibrate the gyroscope and determine the scale factor. The applied rotation rate was swept from 0.02 deg/sec to 10 deg/sec and the scale factor was measured to be approximately 335 mV/deg/sec, as shown in (Figure 4(a)). The performance of the gyroscope was characterized with the setup at rest using an Allan deviation technique (Figure 4(b)). The ARW is characterized from vertical deviation from -0.5 slope line was measured to be 8.52 deg/hr$^{1/2}$. BIS was measured from the flat portion[11] of the Allan deviation plot to be 58.7 deg/hr.



(a) (b)

Figure 4. (a) Rotation rate measurement (b) Allan deviation measurement

4. CONCLUSIONS

We reported the first rotation rate measurements of an interferometric optical gyroscope using an ultra-low loss Si_3N_4 waveguide coil. Despite the short length of the waveguide coil (3 m), the demonstrated gyroscope sensitivity (ARW = 8.52 deg/hr$^{1/2}$) was found to be in the same order as that of a commercial automotive grade sensor (ARW = 5 deg/hr$^{1/2}$)[9]. Reduction of total packaging loss to less than 1 dB (currently 12 dB) will greatly improve the performance of gyroscope and bridge the mismatch between values of measured and simulated sensitivity. Simulations show[7,10] that further improvements in waveguide losses and increase in the waveguide coil length (15 m for optimum ARW[7]) will push the sensitivity down to that of a tactical grade sensor (ARW = 0.3 deg/hr$^{1/2}$)[9]. In conclusion, results show that ultra-low loss waveguide coils offer a promising solution to realize a fully integrated waveguide optical gyroscope (IWOG) that is resilient to several noise factors such as errors related to polarization drift[4, 8].

5. ACKNOWLEDGEMENTS

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