

A METHOD TO EXTRACT AND MODEL STRUCTURAL ASYMMETRIES IN DUAL-SHELL GYROSCOPES TO STUDY FREQUENCY DEGENERACY

Lois Meira Lopez, Danmeng Wang, Austin R. Parrish, and Andrei M. Shkel

Microsystems Laboratory, University of California, Irvine, California, USA

ABSTRACT

We introduced a method to model structural asymmetries present in 3D Glassblown Fused Silica Dual-Shell micro-scale hemispherical resonator Gyroscopes (DSG). The method is based on acquisition of a sequence of high-magnification images which are digitally stitched together to create a combined high-resolution view of the critical features of the DSG. These images are then used to identify and measure structural asymmetries, which are subsequently used to construct a solid 3D model of the resonator with imperfections and followed by a Finite Element Method (FEM) analysis. Frequency mismatches of five devices were used to demonstrate the method, confirming to accurately predict mismatches -varying from 100 to 1000 Hz- for both $n=2$ and $n=3$ wineglass modes. The method presents a non-contact approach for studying the effect of non-idealities in the fabrication process for increasing the yield and quality of devices.

INTRODUCTION

The exceptional performance achieved by macro-scale Hemispherical Resonator Gyroscopes (HRG) [1] has motivated the effort to fabricate these devices on the micro-scale, while maintaining their geometry and characteristics [2], [3]. However, the limited tolerances of traditional micro-fabrication techniques pose a challenge when building 3D micro-structures that meet the required precision and symmetry of high-performance rate-integrating gyroscopes. In conventional MEMS fabrication, imperfections in the lithography, etching, and morphology of the structural material would typically define asymmetries [4]. However, the mechanisms defining asymmetries in the wafer-level glassblowing process are different [5], [6].

The Fused Silica (FS) Dual-Shell micro-scale HRG (DSG) is a novel implementation of the hemispherical resonator concept, showing potential for extremely high quality factor and continuous operation despite mechanical shock, vibrations, radiation, and harsh thermal conditions. The Dual-Shell resonator fabrication process was disclosed in [7] and first demonstrated in [8]. Even though glassblowing on the micro-scale does not fundamentally suffer from traditional sources of asymmetry due to its nature [9], it can introduce new dependencies such as temperature non-uniformity during glassblowing, preferential glass flow relative to gravity, and others. Previous work on glassblown hemispherical resonators, [10], focused on imperfections introduced during the grinding release process, showing that these can cause frequency mismatches on the order of tens of Hz, which can be corrected using directional grinding. It has been shown that Dual-Shell Resonators can achieve low frequency mismatch of only a few Hz as-fabricated, [11]. However, an occasional appearance of larger mismatches, above 100 Hz, was not well understood. Identifying and understanding the source of large asymmetries is critical to increasing yield and quality of the wafer-level fabrication process.

In this paper, we report a method to optically identify, measure, and model structural asymmetries present in the geometry of micro-fabricated DSG. Accurate prediction of a wide range of frequency mismatches demonstrates the effectiveness of this method, providing an insight into possible causes of the asymmetries.

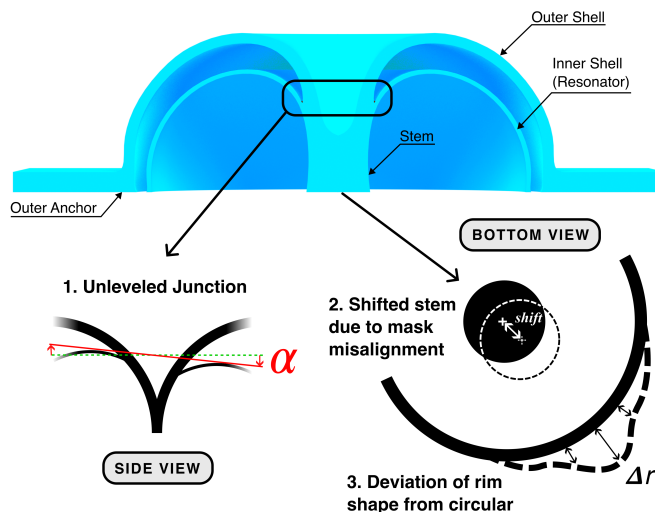


Figure 1: Three types of asymmetries considered in this paper.

METHOD

The Dual-Shell architecture includes an outer shell that serves both as an anchor and a protective casing to the vibrating inner shell (Fig. 1). Such architecture increases robustness of the structure to external shock, shielding it from the environment. However, the multi-shell architecture also makes analysis of the resonator geometry a complex task, due to light reflections, transparency of the material, and the view of the inner shell being obscured from most viewing angles.

To overcome these metrology challenges, devices were analyzed by a high-magnification digital microscope from below (bottom view) and perpendicular to the structure (side view), Fig. 1. The hemispherical resonators used for this study had a device radius of 2.7 mm and rim thickness on the order of 100 μm . For each device, multiple high-magnification (50x), high-resolution (1.17 pixels/ μm) images of the inner shell rim were acquired using a Leica DM6 B digital microscope with Differential Interference Contrasts (DIC) and digitally stitched together using matching features (Fig. 3a). Then, these images were processed using a metrology software from Leica Application Suite (LAS X) to reveal structural asymmetries. In this step, three types of asymmetries were considered: deviation of the rim shape from circular, a shifted stem, and an unleveled junction (Fig. 1).

Deviations of the rim from circularity can be expressed as the changing value of the radius along the symmetry axis of the shell, and this is the first time they were studied. A shifted stem was also studied in [12] for its role in anchor losses, and it is defined as a misalignment between the center of the stem and the center of circumference of the rim. For micro-scale hemispherical resonator gyroscopes, tilting is mainly associated with non-uniform temperature distribution during glassblowing [10] or blow-torching [13]. To measure tilting of the junction, lower resolution side-view images were acquired (Fig. 3b). From this viewing angle, the tilt was observed through the transparent outer-shell.

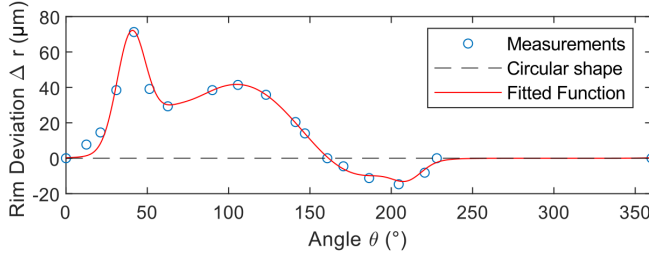


Figure 2: Rim deviation function fitted to measurements for subsequent importing to FEM model. All five devices exhibit similar deviations in varying magnitudes. Device #1 is shown for illustration purpose.

In particular, discrete measurements of rim deviations were fitted to functions of the form:

$$\Delta r(\theta) = \sum_{n=1}^N A_n \sin(\theta/2 + s_n)^{k_n}, \quad (1)$$

where θ is the angle along the central axis of symmetry, A_n is amplitude of the radius error in micrometers, s_n is an angular shift, and k_n is an exponent to tune the sharpness of the deformation. The form of these functions should not be confused with a Fourier transform, which would contain multiple harmonics. The exponential sinusoidal terms were chosen based on their ability to represent aberrations in the radial profile of the rim, thus matching the measurements obtained from metrology when multiple terms are combined (Fig. 2).

The value of each asymmetry was introduced into a parametric finite element solid model in COMSOL Multiphysics software, [14]. The values were applied as prescribed displacements to a symmetric solid 3D model (Fig. 4) obtained from glassblowing simulations, using a non-isothermal glass flow model similar to the one used in [5]. Finally, the asymmetric mesh was exported for subsequent frequency mismatch simulation. The simulation consisted of a solid-mechanics eigenfrequency analysis with the outer anchor and the stem as boundary conditions (fully clamped). It was observed that an insufficiently dense mesh would introduce artificial frequency split in FEM simulations. Therefore, an adequate meshing of the model of $\sim 400,000$ degrees-of-freedom was verified by computing the frequency degeneracy when asymmetries are not present, yielding an accuracy of ± 1 Hz. A higher accuracy can be obtained with a denser mesh, but it wasn't necessary for the magnitude of mismatches considered in this study.

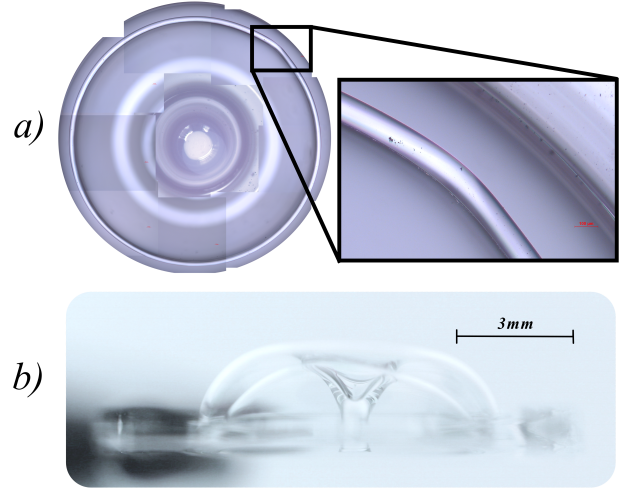


Figure 3: a) Bottom view (Fig. 1) of the rim of DSG resonator. Images are manually stitched into position using overlapping features. b) Side-view of the resonator, where tilt of the junction can be observed and measured.

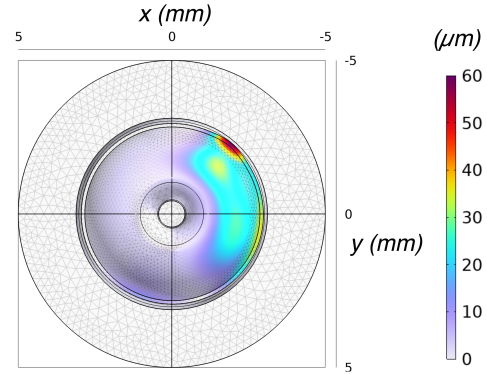


Figure 4: Identified rim imperfections in device #1 transferred to a solid model: the asymmetric COMSOL mesh was used for subsequent frequency analysis. The legend illustrates deviation from an idealized, perfectly symmetric DSG structure.

SIMULATION AND EXPERIMENTAL RESULTS

The frequency mismatches of five different devices were used to demonstrate the methodology. The samples were experimentally analyzed using Laser-Doppler Vibrometry, and compared to the FEM simulation of structures with imperfections. Resonators with varying levels of asymmetry were considered, ranging from 10 to 1000 Hz (Fig. 5).

The FEM modelling approach allowed to look at the relative contribution of each type of asymmetry individually. Fig. 6 shows the frequency split of each device with only one of the asymmetries considered. First, the analysis shows that the asymmetry type generating the most mismatch is the rim deviations from the circular shape, followed by the junction tilt. The stem shift contribution was observed to have a minimal effect. Second, the analysis shows the inter dependencies between asymmetries. Based on their relative orientation (i.e. direction of tilting), the defects can significantly amplify or cancel out each other, and

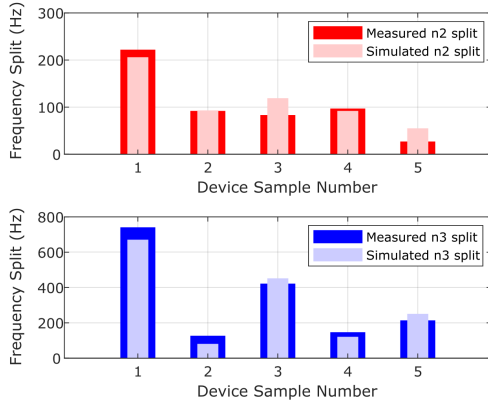


Figure 5: Measured and simulated frequency mismatch for $n=2$ and $n=3$ wineglass modes. The method was applied to a wide range of frequency mismatches.

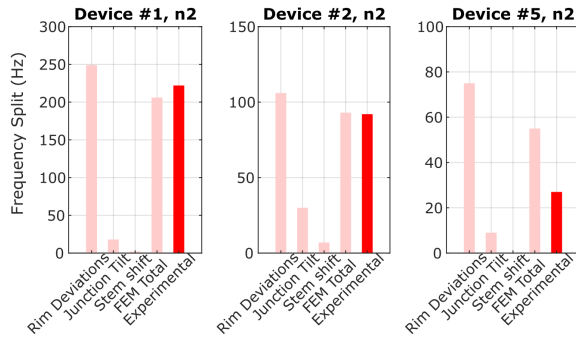


Figure 6: Decomposition of the simulated frequency splits into the different asymmetry types for $n=2$. For $n=3$, it was found that the only contributing asymmetry was the deviations of the rim shape from circular.

therefore cannot be considered independently.

Finally, it has been analytically predicted [15], and shown experimentally [13], that only asymmetry deviations (radius, thickness) of 4th and 6th harmonics will contribute exclusively to frequency degeneracy of $n=2$ and $n=3$ wineglass modes, respectively. Fig. 7 shows the harmonic content of each of the functions (Eq. 1) fitted to the radius variation across each of the devices. As shown, 4th (red regions) and 6th (blue regions) harmonics are present in the error functions. This highlights the necessity to improve the fabrication process to eliminate the corresponding sources of asymmetry which, while random in nature, can introduce 4th and 6th order harmonics and lead to large frequency mismatches.

OUTLOOK AND FUTURE RESEARCH

In this paper, we have identified and analysed structural asymmetries that can lead to large frequency mismatches. However, their origin remains unknown. Each of these asymmetries needs to be linked to non-idealities during fabrication to increase the yield of the wafer-level process. Below are some of the hypothesis to be investigated.

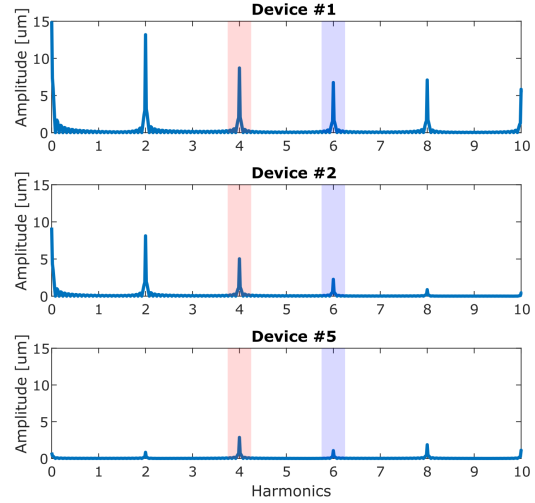


Figure 7: Harmonic content of the functions fitted to radius deviations. Only the 4th and 6th harmonics contribute to frequency split for $n=2$ and $n=3$, respectively, and are highlighted by red and blue regions on the plot.

Junction tilt

The tilting of the junction was observed to introduce a significant mismatch for $n=2$ wineglass mode, but not for $n=3$. It is currently believed that temperature non-uniformity is the main source of tilt in the Dual-Shell resonators, observed in both the inner and outer shells being tilted in the same direction as from the side-view (Fig 3b). Preliminary simulations that consider a non-uniform temperature field across the device show how a gradient of 50°C of the 1500°C glassblowing process can lead to 3-4 degrees of tilting, in line with what has been observed in the fabricated devices (Fig. 8a). To correct this, a custom furnace with higher temperature uniformity is being developed to address the challenge of uniformity.

Radial deviations

The radial deviations have been identified to be the primary fabrication error in glassblown devices. A closer look at the fabricated wafer stack before glassblowing has shed light on the origin of these imperfections. Fig. 8b shows high-resolution SEM pictures of the cavities etched on the glass using isotropic hydrofluoric acid etching. This is a critical step that defines the geometry of the resonator. Medium to large spherical imperfections can be observed on the rim of the cavities, hinting at a deficient masking of the $2\text{ }\mu\text{m}$ polysilicon layer. The reason why the acid has penetrated the mask is still unclear at this point, but glassblowing simulations of such imperfections show that they can lead to radial deviations, such as the ones measured in the fabricated devices. Two different approaches are being considered to remove this source of asymmetry:

- Additional wafer thinning after the HF etching step, to remove the top surface of the wafer most affected by the imperfections.

- Higher temperature and/or higher glassblowing time. Surface tension forces will work towards a symmetric structure if given enough time for structure to develop its shape.

Stem shift

Although shifts in position of the stem have been shown to contribute little to the total mismatch of devices, the cause of this imperfection will be evaluated for reasons beyond frequency degeneracy, such as precise bonding of the stem to an electrode substrate [16], or its possible effect on the anchor loss [12].

Misalignment between wafers of the stack during the plasma-activated bonding could introduce this type of shifting. However, the bonding misalignment of the fabricated devices was measured before glassblowing to be well below the measured shifts, on the order of $5\text{ }\mu\text{m}$, as opposed to stems being shifted by as much as $100\text{ }\mu\text{m}$, in some cases. Not all devices feature this type of imperfection, which would be expected to affect uniformly the whole wafer if it were an alignment-related issue.

Therefore, the most likely cause of shifting and overall stem deformation is hypothesized to be due to non-uniformity of stem bonding, exacerbated by etching related imperfections, like the ones shown in Fig. 8b. Methods for improving bond quality are a topic of ongoing research.

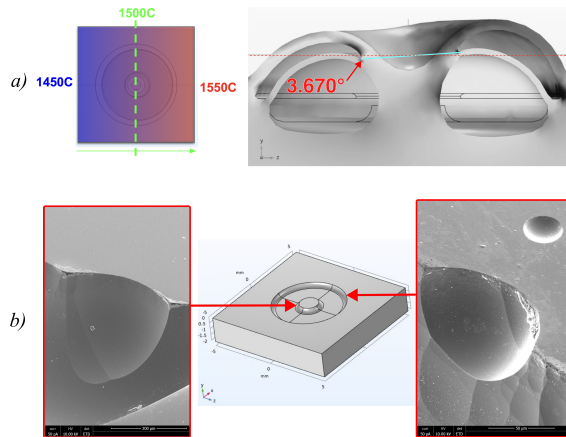


Figure 8: a) Left: temperature gradient used as an input to the 3D Glassblowing simulation. Right: resulting geometry of a Dual-Shell highlighting the exaggerated junction tilt. b) Left/Right: SEM images of defects in the glass caused by deficient masking during hydrofluoric acid etching. Center: schematic view of a typical etched donut cavity for Dual-Shell fabrication.

CONCLUSION

In this study, a modeling approach aided by optical metrology was shown to be a powerful tool for identification of imperfections causing both large and small frequency degeneracy in 3D shell resonators. The identified asymmetries were shown to be the major contributions to mismatch of the fabricated devices, particularly radial deviations and junction tilt. The FEM method allowed to decouple sources of asymmetry, showing how they can have a cancelling effect on each other based on their relative orientation. It was also shown that even localised radial deviations can introduce 4th and 6th harmonic error, known to be direct

cause of fundamental degeneracy, highlighting the importance of improving fabrication tolerances to yield low-mismatch devices that make-up gyroscopes with higher sensitivity and reduced drift.

ACKNOWLEDGMENT

This work was supported by the Integrated Photonics For Sustained Operations under Collaboration Agreement Number: 2022137-142232. The devices were designed and characterized at the UCI Microsystems Laboratory and fabricated at the UCI INRF Cleanroom. SEM images were taken by instrumentation at the UC Irvine Materials Research Institute (IMRI), which is supported in part by the National Science Foundation through the UC Irvine Materials Research Science and Engineering Center (DMR-2011967). We thank Esther Wong, Matthew Alexander Delmont, and Titus De Jong for their help in the release process of resonators.

REFERENCES

- [1] D. M. Rozelle, "The hemispherical resonator gyro: From wineglass to the planets," in *AAS/AIAA Space Flight Mechanics Meeting, Savannah, GA, USA*, February 8-12, 2009.
- [2] "Microscale Rate Integrating Gyroscope (MRIG)". DARPA-BAA-10-39, April 28, 2010.
- [3] D. Senkal and A. M. Shkel, "Whole-Angle MEMS Gyroscopes: Challenges and Opportunities." IEEE Press with John Wiley & Sons, 2020, ISBN-13: 978-1119441885.
- [4] C. Acar and A. Shkel, "MEMS vibratory gyroscopes: structural approaches to improve robustness." Springer Science & Business Media, 2008, ISBN-13: 978-0387095356.
- [5] E. J. Eklund and A. M. Shkel, "Glass blowing on a wafer level," *IEEE/ASME Journal of Microelectromechanical Systems*, vol. 16, no. 2, pp. 232–239, 2007.
- [6] —, "Self-inflated micro-glass blowing," U.S. Patent 8 151 600, Apr. 10, 2012.
- [7] A. M. Shkel, M. H. Asadian, and Y. Wang, "Fused quartz dual-shell resonator and method of fabrication," U.S. Patent 11 703 330, Jul. 18, 2023.
- [8] M. H. Asadian and A. M. Shkel, "Fused quartz dual-shell resonator," in *IEEE International Symposium on Inertial Sensors and Systems (INERTIAL)*, Naples, FL, USA, April 1-5, 2019.
- [9] D. Senkal, M. J. Ahamed, A. A. Trusov, and A. M. Shkel, "Achieving sub-Hz frequency symmetry in micro-glassblown wineglass resonators," *IEEE/ASME Journal of Microelectromechanical Systems*, vol. 23, no. 1, pp. 30–38, 2014.
- [10] Y. Wang, M. H. Asadian, and A. M. Shkel, "Compensation of frequency split by directional lapping in fused quartz micro wineglass resonators," *Journal of Micromechanics and Microengineering*, vol. 28, no. 9, p. 095001, 2018.
- [11] M. H. Asadian, D. Wang, and A. M. Shkel, "Fused quartz dual-shell resonator gyroscope," *IEEE/ASME Journal of Microelectromechanical Systems*, vol. 31, no. 4, pp. 533–545, 2022.
- [12] A. Darvishian, B. Shiari, J. Y. Cho, T. Nagourney, and K. Najafi, "Anchor loss in hemispherical shell resonators," *IEEE/ASME Journal of Microelectromechanical Systems*, vol. 26, no. 1, pp. 51–66, 2017.
- [13] B. Li, X. Xi, K. Lu, Y. Shi, D. Xiao, and X. Wu, "Frequency split improvement of fused silica micro shell resonator based on suppression of geometric harmonic error," in *IEEE International Symposium on Inertial Sensors and Systems (INERTIAL)*, Hiroshima, Japan, March 23-26, 2020.
- [14] COMSOL Multiphysics® v. 6.2. www.comsol.com. COMSOL AB, Stockholm, Sweden.
- [15] B. S. Lunin, "Physical and chemical bases for the development of hemispherical resonators for solid-state gyroscopes," Moscow: Moscow Aviation Institute, Technical Report, 2005.
- [16] D. Wang, M. H. Asadian, D. Hii, and A. M. Shkel, "Fused silica dual-shell gyroscope with in-plane actuation by out-of-plane electrodes realized using glassblowing and thru-glass-vias fabrication," in *IEEE International Conference on Micro Electro Mechanical Systems Conference (MEMS)*, Avignon, France, May 8-11, 2022.