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Development of microscale 3D fused quartz hemi-toroidal shells for high-Q resonators and gyroscopes

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Introduction

3D Fused Quartz (FQ) shells offer mass, stiffness, and damping symmetry, as well as structural rigidity, for the sensing element of Coriolis Vibratory Gyroscopes (CVG). A precisely machined and polished hemispherical shell is the core of a Hemispherical Resonator Gyroscope (HRG) [1]. The outstanding performance of HRG has originated from its highly symmetric hemispherical structure with an extraordinarily Q-factor (>25 million), and has motivated the development of batch fabrication and miniaturization of 3D shell resonators, utilizing Micro-Electro-Mechanical Systems (MEMS) fabrication techniques.

The fabrication processes to realize MEMS-based 3D resonators and gyroscopes can be classified into two main categories: (1) thin-film shell resonators and (2) bulk-deformed shell resonators. In the former, thin film structural and sacrificial materials were deposited on pre-etched hemispherical cavities or precision microspheres, and the shell resonators were released by removal of the sacrificial material. Polysilicon [2], silicone dioxide [3], Ultra-Low Expansion (ULE) glass [4], microcrystalline diamond [5], and an Iron-Nickel alloy (Invar) were used as the structural material for thin-film shell resonators. The thickness of thin-film shell resonators was limited by the maximum thickness allowance to achieve a low-stress thin-film deposition, hence, it was limited to just a few microns. The bulk-deformed shell resonators were fabricated based on a high-temperature thermo-plastic deformation of the structural materials such as borosilicate glass, Bulk Metallic Glass (BMG), ULE glass, and Fused Quartz (FQ).

Micro-glassblowing process was initially developed for wafer-level fabrication of microspherical glass cells for nuclear magnetic resonance (NMR) atomic sensors. In this process, a cavity was etched using Deep Reactive Ion Etching (DRIE) in a Silicon substrate wafer, and encapsulated by Si-to-glass anodic wafer bonding. At the glassblowing temperature (~ 850 °C), the pressure builds up inside the encapsulated cavity while simultaneously the viscosity of glass decreases. The viscous glass layer expands, while the surface tension force minimizes the surface area and forms 3D spherical shells. The process was adapted for the fabrication of microspherical and inverted wineglass shell resonators. In the FQ glassblowing process, the cavities were etched on a FQ wafer and encapsulated by plasma-assisted FQ-to-FQ wafer bonding. Since FQ has a higher softening temperature compared to borosilicate glass, the glassblowing occurs at temperatures greater than 1500 °C. Hemi-toroidal FQ shell resonators with a broad range of operational frequencies were fabricated using the high-temperature micro-glassblowing process. In this work, we report the design optimization and process developments for fabrication of high-Q FQ shell resonators with a broad range of operational frequencies, and demonstrate a feasibility for implementing an array of FQ shells fabricated using the batch fabrication microglassblowing process.

Methods

A. Scaling of modal resonant frequency

Similar to any continuous structural systems with distributed mass and stiffness, such as beams, rings, plates, and membranes, a hemi-toroidal (or hemispherical) geometry has an infinite number of orthogonal modes of vibration. An input rotation along the axis of symmetry of shell resonators couples (any) degenerate wineglass modes through the Coriolis acceleration, and can be configured to detect the rotation rate (rate gyro) or the absolute angle of rotation (whole angle gyro). The n = 2 wineglass mode is considered to be a preferable structural mode for operation due to a higher angular gain, which is a measure of sensitivity of the whole angle gyro.

B. Effect of Shell geometry on Modal Frequency Separation

The shell radius, thickness, and anchor radius are the design parameters that define the geometry of a hemi-toroidal shell. Using a series of parametric FE modal simulations, the shell thickness, radius, and anchor radius were varied from 40 um to 150 um, 2.5 mm to 5 mm, and 100 um to 500 um, respectively, generating more than 200 design combinations. The n=2 wineglass resonance frequency and the frequency separation with the closest parasitic mode at different design points were identified. The design space demonstrates that for a wineglass frequency of interest, a shell resonator can be obtained from a different combination of design parameters. Also, it indicates that separation between spurious and operational modes depends on selection of the geometric parameters. The result demonstrated a possibility of ordering the resonance modes of a shell resonator, with
spurious modes at higher resonance frequencies, as compared to the frequency of n=2 wineglass mode, which is an important consideration for avoiding the environmental excitation of the device during operation. The red data points in Fig. 5 refer to cases where the mode-ordering condition is satisfied, and n=2
wineglass mode has the lowest resonance frequency.

Results

The effect of shell geometrical parameters on the modal frequency and ordering on the resonance modes were experimentally studied. The mode shape identification was performed using a servo-motor controlled rotary stage. The assembled shell on the piezo stack was mounted on the rotary stage and the amplitude of vibration was measured using a Laser Doppler Vibrometer (LDV) at incrementally spaced azimuth angles at each peak frequency, to identify the corresponding mode shapes.

The frequency response of a shell with thickness = 45 um, shell radius = 4.25 mm, and anchor radius = 500 um was tested. The N=2 wineglass mode was identified at 5.7 kHz as the first vibration mode with a minimum frequency separation of 2 kHz to the nearest spurious mode (tilt). The experimental results demonstrated that frequency separation and mode-ordering could be achieved through the parameters of the shell geometry, at the operational frequency of interest.

Conclusions & Contributions

A comprehensive design and fabrication process of fused quartz hemi-toroidal shell resonators were presented. A design space for shell geometric parameters was constructed to increase the frequency separation between the n=2 wineglass operational mode and spurious modes. The possibility of ordering the resonance mode in the shell resonators only through the selection of proper geometric parameters was discussed. The dependency of QTED on the shell geometry (thickness and diameter) were numerically analyzed. The presented procedure revealed that a mode-ordered shell resonator with a large operational/spurious frequency separation and high QTED could be achieved through the design of shell geometry. An example set of parameter for an operational frequency of 10 kHz was provided. A finite element method based on an isothermal fluid flow model was presented for the simulation of the glassblowing process. The simulations were used to determine the initial process parameters, and to predict the final geometry of the glassblown shells.

The developed micro glassblowing processes would enable a low-cost and highly-flexible fabrication of high-Q fused quartz micro shells, which can be implemented as a core sensing element with a compact form factor in micro-resonators and
Coriolis vibratory gyroscopes for precision navigation and timing applications.

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Abstract Summary

In this paper, recent developments in design and fabrication of micromachined fused quartz hemi-toroidal shells are presented. The fabrication is based on micro glassblowing process, demonstrated to enable realization of high-Q MEMS resonators and gyroscopes. The design optimization of the shell geometry is performed using parametric finite element analysis, and the effect of geometrical parameters on the scaling of the resonant frequencies and energy dissipation are discussed. Three variations of the micro-glassblowing process are studed in the paper, concluding that shell resonators with a broad operational frequency range without losing the symmetry and Q-factor are feasible. Finite element models are presented to simulate the presented glassblowing processes, which is used to accurately predict the final geometry of shell resonators. Operational frequency as low as 5 kHz and Q-factor as high as 1.7 million are demonstrated on the fabricated shell resonators. The proposed process modifications demonstrate a low-cost and scalable fabrication of 3D shells for resonators and gyroscopes which can be used in inertial navigation and timing applications.

Keywords

3D MEMS, Shell Resonators, Gyroscopes, Fused Quartz, Precision Assembly