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Three-Dimensional Spherical Shell Resonator Gyroscope Fabricated Using Wafer-Scale Glassblowing

Sergei A. Zotov, Alexander A. Trusov, and Andrei M. Shkel

***Abstract*—We report, for the first time, experimental demonstration of a 3-D spherical shell resonator microelectromechanical systems gyroscope fabricated using wafer-scale glassblowing. The gyroscope utilizes a 1-mm-diameter 10-μm-thick spherical isotropic shell surrounded by eight cofabricated satellite spheres serving as actuation and detection electrodes. To demonstrate functionality of the new device, a four-node wineglass mode at a 945-kHz frequency was utilized as the drive mode of a Coriolis vibratory gyroscope. The input rotation causes the transfer of energy from the drive mode to the sense mode, which is a complementary four-node wineglass mode oriented at a 45° angle. Sense-mode vibrations were capacitively detected using cofabricated 3-D metal electrodes. Experimental characterization of the spherical shell gyroscope demonstrated a wide linear range of 1000°/s, currently limited only by the experimental setup. [2011-0327]**

***Index Terms*—Glassblowing, gyroscope, 3-D microelectromechanical systems (MEMS) spherical shell.**

I. Introduction

One of the most successful implementations of a Coriolis vibratory gyroscope is the Northrop Grumman Hemispherical Resonator Gyroscope (HRG) [1], which utilizes inertial precession of a standing wave in an axisymmetric and isotropic resonator shell. While the device achieves higher-than-inertial-grade performance, the cost per single axis is extremely high due to the precision machining and assembly of multiple fused silica components. The manufacturing technology also does not provide a path to device miniaturization. The need for wafer-level manufacturable spherical shell microsensors motivates the current research. The recently introduced wafer-scale glassblowing [2], as well as other novel fabrication technologies [3], [4], shows potential for manufacturing of high-quality 3-D spherical microelectromechanical systems (MEMS) structures, which could take advantage of the HRG sensor physics. The purpose of this letter is to demonstrate for the first time the feasibility of a MEMS 3-D spherical shell resonant gyroscope fabricated using wafer-scale glassblowing.

II. Spherical Gyroscope Concept

The proposed microspherical resonator gyroscope comprises a glass-blown spherical resonator shell and capacitive transducers formed by conductive metal films on 3-D surfaces, as shown in Fig. 1. The fabrication process starts by hermetically bonding a Pyrex glass wafer to a silicon wafer with pre-etched arrays of cylindrical cavities under normal atmospheric conditions. The wafer stack is then heated above 850 °C to decrease the viscosity of glass and create gas pressure inside the air pockets sealed at room temperature. The combined effect of glass softening, surface tension, and internal gas pressure results in the glassblowing of 3-D spherical structures with embedded metal electrodes having a gap of 5 μm, as shown in Figs. 2 and 3.

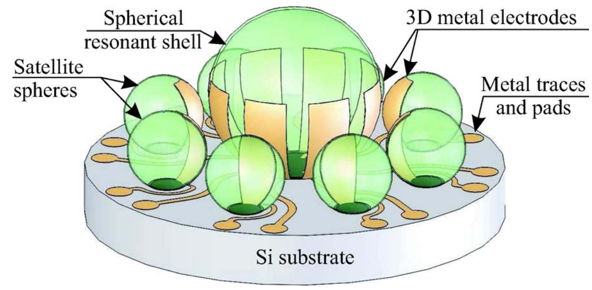

Fig. 1. Conceptual schematic of a 3-D MEMS spherical shell gyroscope with cofabricated transduction electrodes.

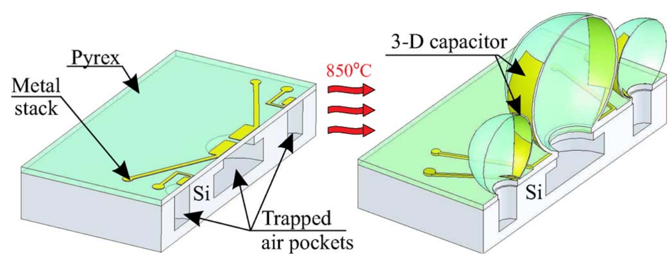

Fig. 2. Fabrication approach for the 3-D MEMS spherical gyroscope using wafer-scale glassblowing of a glass layer with a patterned metal stack.

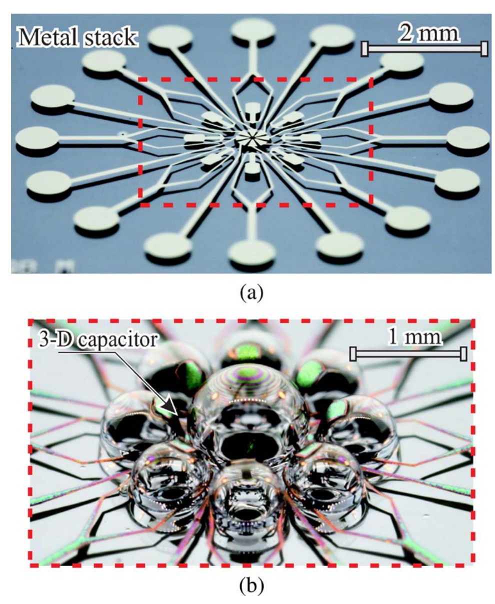

Fig. 3. Photographs of a fabricated spherical microgyroscope with embedded transduction. Actuation and detection capacitors are created using the satellite spheres. (a) Flat structures before glassblowing. (b) Spherical structures after glassblowing.

III. Experimental Characterization

For the experimental characterization of structural mode shapes, a 3-D spherical gyroscope die was bonded to a piezoelectric plate

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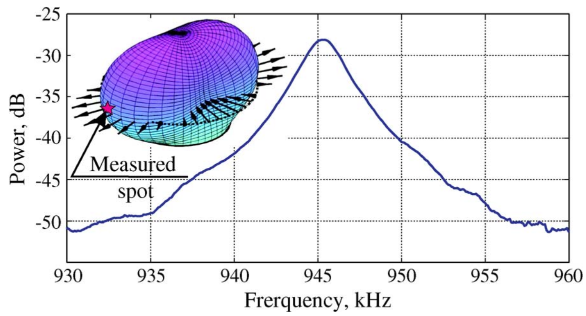

Fig. 4. Measured frequency response of a 945-kHz four-node wineglass mode used as the drive mode of the spherical shell MEMS gyroscope. (Inset) FEM of the four-node wineglass mode.

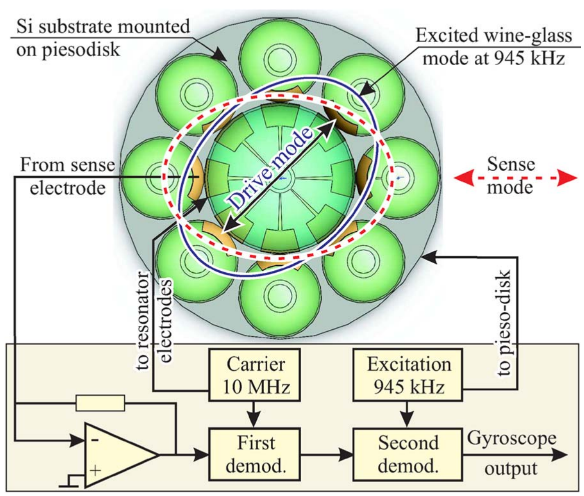

Fig. 5. Schematic of the experimental setup for angular rate characterization of the spherical MEMS gyroscope with piezoelectric actuation and on-chip detection.

actuator. A Polytec OFV-5000 single-point laser Doppler vibrometer was used to directly measure velocities of equatorial surface points on the vibrating shell [5], [6]. Analysis of the vibrational amplitudes of the equatorial surface points revealed a four-node wineglass mode at a 945-kHz frequency. The relative frequency mismatch $\Delta f/f$ between the two degenerate four-node wineglass modes was measured as 0.7%. A measured frequency response of one of the four maximum displacement points (antinodes) of the four-node wineglass mode is shown in Fig. 4. The angular rate performance of the microspherical resonator gyroscope was experimentally characterized in air by applying a rotation stimulus with an Ideal Aerosmith Model 2102 precision rate table. The four-node wineglass drive mode was excited into resonance at 945 kHz with an amplitude of 0.04 μm by applying a 10-Vac drive voltage to the bonded piezoelectric substrate. Several alternative principles of excitation of the spherical resonator have been published in detail [5]. The sense-mode motional current was detected capacitively using a cofabricated 3-D capacitor and converted to a voltage using a transimpedance amplifier.

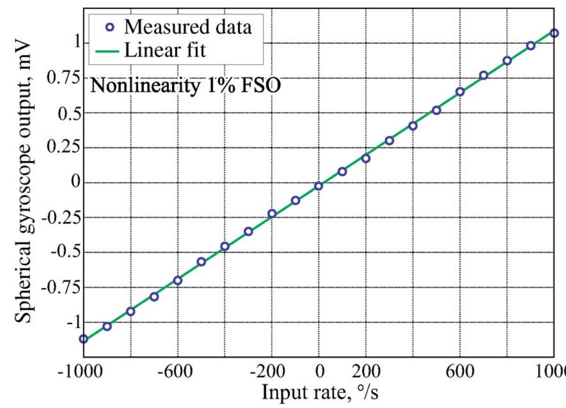

Fig. 6. Experimental characterization of the rate response, demonstrating an input–output linearity of the 3-D spherical shell MEMS gyroscope fabricated using wafer-level glassblowing.

The rotation rate is measured using electromechanical amplitude modulation to detect the small output signal from the gyroscope compared to the environmental noise level [7]. The carrier frequency utilized is 10 MHz, which is much greater than the operational frequency of the gyroscope and thus has negligible effects on the proof mass dynamics. The sensor output signal is amplified using a transimpedance amplifier, followed by demodulation at the carrier frequency. The sense-mode signal was then demodulated at the drive frequency to extract the Coriolis force response signal, as shown in Fig. 5. The measured rate response of the 3-D MEMS spherical shell resonator gyroscope in a $1000^\circ/\mathrm{s}$ range is shown in Fig. 6, demonstrating a rate sensor with a linear input–output relationship.

Our preliminary results demonstrate the feasibility of the glassblowing approach for batch manufacturing of 3-D MEMS gyroscopes and motivate further research into optimization of the device geometries and use of glasses with low internal loss of mechanical energy as alternative structural materials.

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