Characterization of Energy Dissipation Mechanisms in Dual Foucault Pendulum Gyroscopes

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***Abstract*—In this paper, the primary energy dissipation mechanisms in a dynamically balanced Dual Foucault Pendulum (DFP) gyroscope are identified and characterized experimentally. A Q-factor over one million was measured at room temperature on a vacuum packaged mode-ordered DFP, with operational frequency at 15 kHz. The measurement at low temperature, using a cryogenic probe station, made the anchor loss limit of Q-factor observable. A Q-factor of over 9 million was measured at 110K. The unbalanced electrostatic softening due to fabrication imperfection was identified to contribute to the anchor loss.**

I. Introduction

Microelectromechanical Systems (MEMS) gyroscopes with multi-degrees of freedom can be configured to improve sensitivity, bandwidth, and vibration immunity [1]. The MEMS vibratory gyroscopes with two (or more) masses and operating in the anti-phase resonance mode, would mitigate the energy dissipation through the substrate by balancing the total forces and moments acting on the anchors. Thus, dynamically balanced designs improve the quality factor, resulting in a higher sensitivity and improved in-run noise performance.

A Dual Foucault Pendulum (DFP) is a lumped mass-spring type gyroscope which consists of two identical masses and four pairs of identical suspension elements, providing X-Y structural symmetry [2], as well as ordering of the in-phase and anti-phase resonance modes [3]. The DFP is believed to provide the minimal realization of a mode-matched dynamically balanced lumped mass gyroscope.

In this paper, a mode-ordered DFP device, fabricated on a Silicon-on-Insulator (SOI) wafer using the epitaxial silicon encapsulation process (EpiSeal), is utilized for identification and characterization of energy dissipation mechanisms. The device under test was vacuum sealed with getter activation, as described in [3].

II. Thermoelastic damping (TED)

A Finite Element Analysis (FEA) of TED was performed with a coupled thermal-mechanical model using COMSOL Multiphysics FEA package. The model predicted a Q-factor of 1.18 million for the anti-phase resonance mode. The as-fabricated Q-factor of 130,000 was limited by the air damping at the encapsulation cavity pressure (0.3 mTorr [4]). The Q-factor reached 820,000 after venting the cap layer and measuring in a vacuum chamber at 20 μTorr. A Q-factor of 1.15 million was measured after vacuum sealing with getter activation, which is in strong agreement with predictions of the TED model, Fig. 1. The viscous damping was effectively

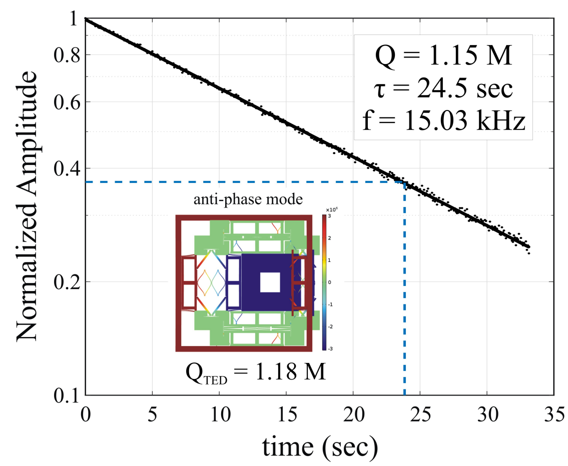

Fig. 1. Experimental measurement of the amplitude decay time demonstrating 1.15 million Q-factor in a vacuum sealed (with getter) mode-ordered DFP gyro, approaching the theoretical TED limit of the design.

suppressed by vacuum packaging using an ultra-high vacuum sealing process, [5], achieving the Q-factor at the TED limit.

According to a simplified cantilever beam model by Zener [6], the Q_{TED} strongly depends on the Coefficient of Thermal Expansion (CTE) of the resonator's material. Since the CTE of Silicon depends on temperature, TED can be controlled by temperature and can be effectively eliminated when the CTE crosses zero [7].

A cryogenic probe station (Lake Shore FWP6) was used for the measurements at low temperature. The sealed DFP device was cooled down to 80K, and the Q-factor was measured along both X- and Y- axes of the gyroscope. Fig. 2 demonstrates that Q-factor increases at low temperature and approaches its peak value near 110K. At this temperature, where the viscous damping and the TED are eliminated, the Q-factor reaches 9.29 million. Moreover, the Q-factor measurements for X- and Y-axis demonstrate the inherited damping symmetry in the DFP device.

III. Anchor loss

In an ideal DFP gyroscope, the proof masses move in the opposite direction with the same amplitude in the anti-phase mode along each axis, minimizing the reaction forces and moments on anchors. However, fabrication imperfections would disturb symmetry of the structure and increase the dissipation of energy through the substrate. Fig. 3 illustrates a schematics of one axis of a non-ideal DFP, where masses (m),

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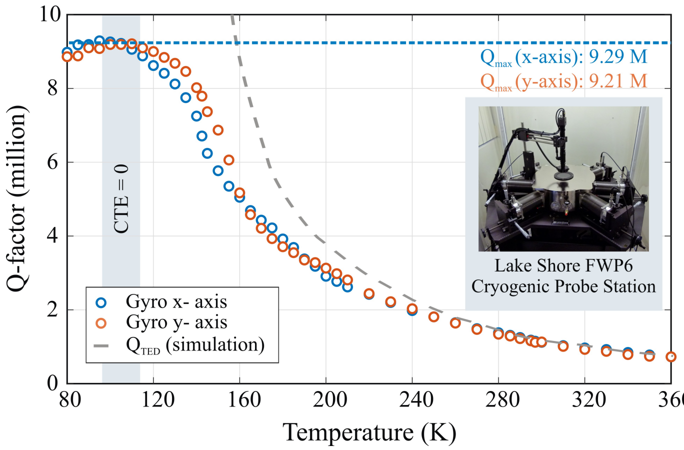

Fig. 2. Experimental measurement of the Q-factor for DFP gyro as a function of temperature. At the peak of the curve, TED is eliminated, and unmasked anchor loss is observed. Inset figure shows the cryogenic probe station which was used for the measurements.

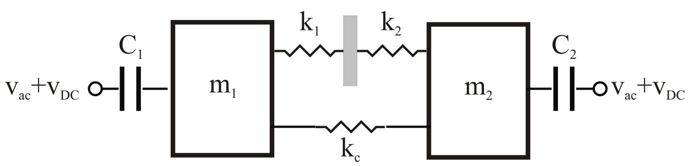

Fig. 3. Schematics of one axis of a non-ideal DFP showing the unbalanced mass ($m_1 \neq m_2$), stiffness($k_1 \neq k_2$), and capacitance ($C_1 \neq C_2$), all due to fabrication imperfections.

stiffness (k), and capacitance (C) of two proof masses are not identical. The capacitance mismatch imposes an unbalanced electrostatic softening, deteriorating the balanced anti-phase motion. Fig. 4 demonstrates the effect of the drive DC bias on the amplitude ratio at different mismatch conditions due to varying capacitive gaps. The Q-factor of the DFP device was measured under different drive DC voltages at 110K and 300K. In all cases, the drive amplitude was fixed to avoid nonlinearities in the drive motion. At 110K, the Q-factor drastically reduced as the voltage increased, whereas it only reduced by 10% at room temperature. The sensitivity of Q-factor to the unbalanced motion proves that at 110K, where the TED and viscous damping are effectively eliminated, the Q-factor of 9.29 million is the anchor loss limit of the DFP device under test.

IV. Conclusion

The energy dissipation mechanisms of a mode-ordered dual Foucault pendulum gyroscope were analyzed. At room temperature, a close match between the measured Q-factor and simulated thermoelastic damping limit was achieved after vacuum sealing with getter activation. The peak Q-factor value of 9.29 million at low temperature revealed an exceptional anchor loss limit, which is attributed to a fully dynamically balanced architecture of DFP. The unbalanced electrostatic softening was identified as the contributing factor to the anchor loss. The sensitivity of the Q-factor to stiffness unbalance was analyzed to identify the primary energy dissipation mechanisms at different temperatures.

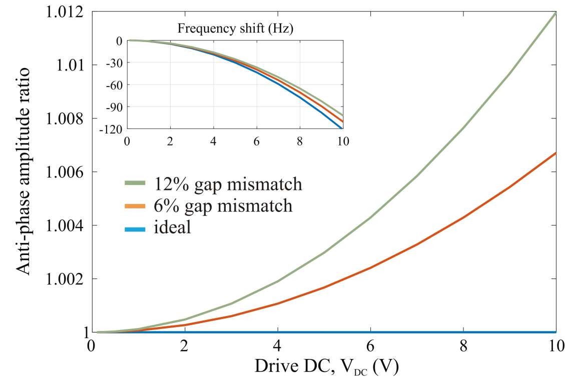

Fig. 4. Effect of unbalanced electrostatic softening on the anti-phase amplitude ratio at different levels of capacitive gap nonuniformity. The inset figure shows the frequency tuning effect. (simulations were based on extracted parameters from the device under test.)

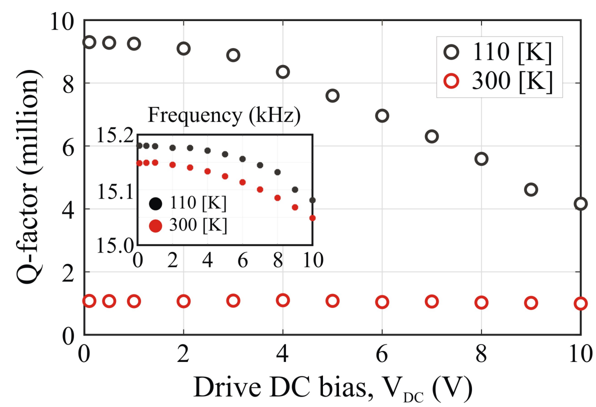

Fig. 5. Experimental measurement of the Q-factor at 110K and 300K at different drive DC biases. At 110K, the Q-factor is sensitive to the motion unbalance imposed by non-uniform stiffness softening, inset figure shows a similar the frequency tuning effect at 110K and 300K.

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