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A multiple-beam tuning-fork gyroscope with high quality factors

Ren Wang[a], Peng Cheng[a], Fei Xie[a], Darrin Young[b], Zhili Hao[a,*]

[a] Department of Mechanical and Aerospace Engineering, Old Dominion University, Norfolk, VA, United States
[b] Department of Electrical and Computer Engineering, University of Utah, Salt Lake City, UT, United States

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ABSTRACT

This paper presents the design, theoretical analysis, fabrication, and experimental results of a multiple-beam tuning-fork gyroscope (MB-TFG). Based on a numerical model of thermoelastic damping, a multiple-beam tuning-fork structure is designed with high quality factors (Q_s) in its two operation modes. A comprehensive theoretical analysis of the MB-TFG design is conducted to relate the design parameters to its operation parameters and further performance parameters. In conjunction with a mask that defines the device through trenches to alleviate previously identified severe fabrication effect on anchor loss, a simple one-mask fabrication process is employed to implement this MB-TFG design on silicon-on-insulator wafers. Experimental results of the fabricated MB-TFGs are thoroughly compared with the theoretical analysis for accurate interpretation. The highest measured Q_s of the fabricated MB-TFGs in vacuum are 255,000 in the drive-mode and 103,000 in the sense-mode, at a frequency of 15.7 kHz. Under a frequency difference of 4 Hz between the two modes (operation frequency is 16.8 kHz) and a drive-mode vibration amplitude of 3.0 μm, the measured rate sensitivity is 80 $\mu V_{PP}/^{\circ}/s$ with an equivalent impedance of 2.5 MΩ. The calculated overall rate resolution of this device is $0.37^{\circ}/h/\sqrt{Hz}$, while the measured angle random walk (ARW) and bias instability are $6.67^{\circ}/\sqrt{h}$ and 95°/h, respectively.

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1. Introduction

Since one of the first micromachined tuning-fork gyroscopes was demonstrated by Draper laboratory in the early 1990s [1], tuning-fork gyroscopes have attracted a great deal of attention, due to its promising design features for high-precision performance and relative ease with fabrication [2,3]. A tuning-fork gyroscope is based on Coriolis effect, in which the vibration energy of a tuning-fork structure is transferred from one vibration mode to another in response to a rotation rate signal in the environment. The key performance parameters of a gyroscope include rate resolution, rate sensitivity (or scale factor), bias drift, and operation bandwidth. In recent years, tuning-fork gyroscopes in various derived forms have been designed and implemented using either surface micromachining technology [4,5] or bulk micromachining technology [6–12] for performance improvement.

To date, many tradeoffs between a gyroscope design and the above-mentioned performance parameters have been identified. For instance, high quality factors (Q_s) in its two modes and matched-mode operation are critical for a tuning-fork gyroscope to achieve high-precision performance [2,6,7,10], including high rate sensitivity, improved rate resolution, and lower bias drift. Therefore, tuning-fork gyroscopes with high Q_s and matched-mode operation have been pursued [6,7,10]. However, such high-precision performance is typically obtained with a narrow operation bandwidth [6]. In contrast, a tuning-fork gyroscope with a wide bandwidth usually needs to sacrifice its rate sensitivity and bias drift [10,11].

Numerous papers have reported on various micromachined tuning-fork gyroscopes [1–12]. The related fabrication technologies and experimental results are mostly described in great details. Conversely, a comprehensive theoretical analysis of a tuning-fork gyroscope, which relates its design parameters to the operation parameters (e.g., drive-mode vibration amplitude and motional resistance) and further the key performance parameters, is typically neglected in the literature. After all, the ultimate performance of a tuning-fork gyroscope is a combined result of its design and operation parameters. A comprehensive description that relates a gyroscope design and its operation to its experimental data is necessary for verifying the design and accurately interpreting the measured performance.

This paper presents a multiple-beam tuning-fork gyroscope (MB-TFG) with high Q_s in its two modes. As compared to the related previous studies [6,7,13], the original contributions of this work include: (1) a multiple-beam tuning-fork structure (MB-TFS) designed with high Q_s in its two operation modes, through utilizing a numerical model of thermoelastic damping based on a thermal-energy method; (2) a comprehensive theoretical analysis relating

* Corresponding author. Tel.: +1 7576836734; fax: +1 7576835344.
E-mail address: zlhao@odu.edu (Z. Hao).

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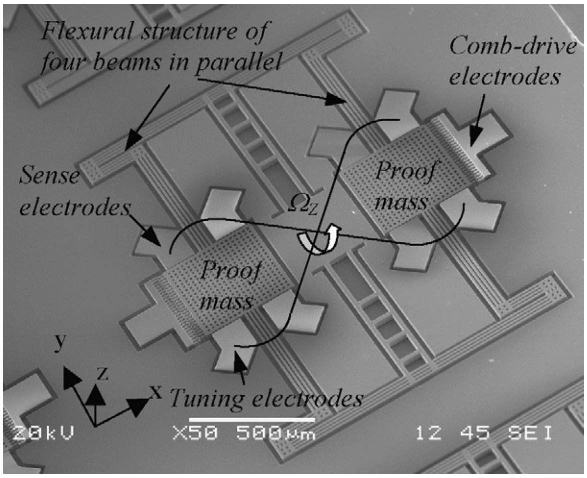

Fig. 1. A SEM picture of the multiple-beam tuning-fork gyroscope (MB-TFG) design.

the design parameters to the operation parameters and further the key performance parameters; (3) a mask that defines the device through trenches for alleviating the severe fabrication effect on anchor loss of the MB-TFS [13]; (4) a thorough comparison between the theoretical analysis and the experimental data of the MB-TFG for verifying the design and accurately interpreting the measured results.

The rest of the paper is organized as follows. In Section 2, the design of the MB-TFG is introduced, together with the details about the MB-TFS with high Q_s in its two modes. Section 3 describes a comprehensive theoretical analysis of the MB-TFG that relates the design parameters to the operation parameters and further the performance parameters. Section 4 presents a simple one-mask fabrication process for fabricating the MB-TFG. In Section 5, a thorough comparison between the experimental data of fabricated MB-TFGs and the theoretical analysis is reported, together with a performance summary of the MB-TFG. Section 6 concludes important results of this work.

2. Design

Fig. 1 shows a SEM picture of a multiple-beam tuning-fork gyroscope (MB-TFG) design for z-axis rotation detection. The multiple-beam tuning-fork structure (MB-TFS) is comprised of two large proof masses and a flexural structure of four beams in parallel. The flexural structure functions as mechanical springs along the x-axis and the y-axis. The whole structure is fixed on the substrate through the anchor located at its center. A collection of electrostatic electrodes is distributed around the proof masses. The MB-TFS is operated in two in-plane vibration modes: one along the x-axis (drive-mode) and the other along the y-axis (sense-mode), as illustrated in Fig. 2. The working principle of this gyroscope is based on Coriolis effect. The comb-drive electrodes are employed to establish vibrations in the drive-mode. A rotation rate signal, Ω_Z, normal to the device plane (z-axis) induces a Coriolis acceleration along the y-axis and excites vibrations in the sense-mode. The resulting vibration amplitude of the sense-mode is then picked up by the four parallel-plate sense electrodes along the y-axis, and the rotation rate signal is extracted. To increase its rate sensitivity and compensate for fabrication variations, a DC tuning voltage is applied on the four parallel-plate tuning electrodes to reduce the frequency difference between the drive-mode and the sense-mode, so that the rate sensitivity can be roughly amplified by a factor of the Q in the sense-mode.

Table 1
Summary of the key design parameters of the MB-TFG.

	Value	Symbol	Unit
Thickness	30	h	μm
Beam width	10	b	μm
Dimension of a proof mass	400 × 400	-	μm^2
Number of comb fingers	25	n	-
Gap between fingers	4	g	μm
Initial sense/tuning capacitance	0.046	C_{S0}/C_{T0}	pF
Sense/tuning gap	3	d_{S0}/d_{T0}	μm
Width of the sense/tuning electrodes	130	W_e	μm
Number of the sense/tuning electrodes	4	n_S/n_T	-

Table 1 summarizes the key design parameters of the MB-TFG. The in-plane dimension of the proof masses is 400 μm × 400 μm and the beam width of the flexural structure is 10 μm. The device will be fabricated on a 30 μm-thick device layer of a silicon-on-insulator (SOI) wafer, and thus the thickness of the MB-TFG is 30 μm. The key design parameters of the electrostatic electrodes are illustrated in Fig. 3(a). The minimum design feature is 3 μm at the sense gap and the tuning gap between the parallel-plate electrodes and the proof masses. Note that the tuning electrodes and the sense electrodes have the identical design dimension. The SEM pictures in Fig. 3(b) and (c) illustrate the actual sense/tuning gap and the gap between comb fingers, respectively. Obviously, the fabricated dimensions are much larger, due to fabrication imperfections.

The MB-TFS employed in the gyroscope is designed with an operation frequency above 10 kHz to avoid any environmental noise [8] and below 20 kHz to keep the operation voltage at a rela-

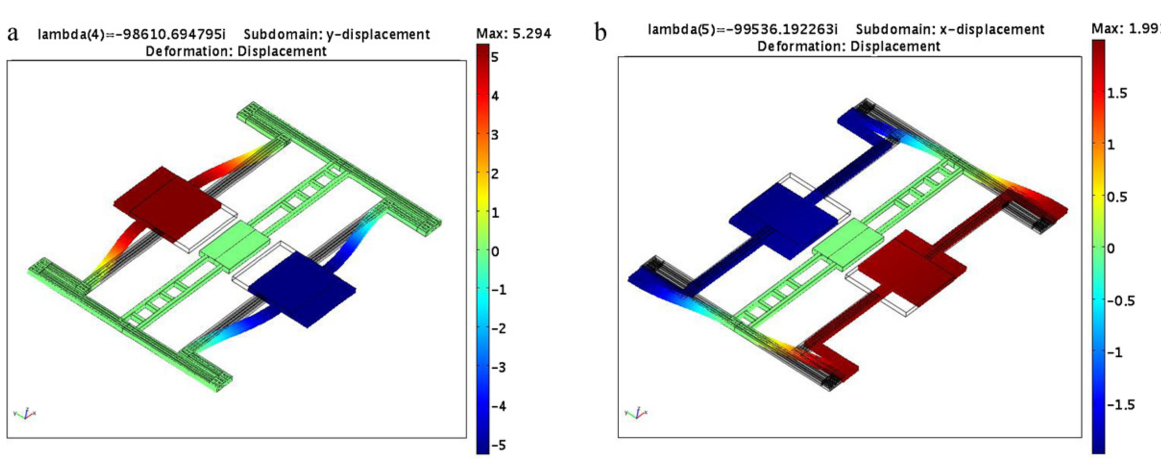

Fig. 2. Two simulated vibration modes of a multiple-beam tuning-fork structure (MB-TFS) (a) drive-mode and (b) sense-mode.