Design and Simulation of a Dual-Mode Resonant Temperature sensor Based on MEMS Technology

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ABSTRACT:
In this paper, a dual-mode (DM) micromechanical elliptical ring resonator for use in temperature sensing is reported. The proposed resonator is made of single crystal silicon and works based on beat frequency (f_b). In the designed sensor, temperature coefficient of beat frequency (TCf_b) will be increased significantly by minimizing the f_b and provides better temperature sensitivity. This proposed device was designed and simulated by COMSOL Multyphysics software. By engineering the device geometry, we introduce two adjacent resonant frequencies which produce very small f_b in the range of 2 kHz. The device shows TCf_1 of about 44 ppm/ºC and TCf_2 of 5 ppm/ºC. Combination of small f_b and large ΔTCf, present temperature coefficient of beat frequency (TCf_b) about 112000 ppm/ºC which has approximately 75× improvement in TCf_b compared to previous demonstrated DM resonators.

KEYWORDS: Temperature Sensing, Dual-mode (DM) Resonator, Beat Frequency, Microelectromechanical Systems, MEMS.

1. INTRODUCTION

During the past decades, Silicon Microelectromechanical resonators (MEMS) have been developed because of their extremely wide range of applications as well as their advantages over the quartz crystal. The major plus points of the silicon MEMS resonators are small size, high resonance frequencies, slower aging, low cost and easy integration with the interface circuitry.

The MEMS system applications have included filter [1], resonant sensors [2], such as strain sensors [3], inertial sensors such as accelerometers [4], mass sensors [5], temperature sensors [6], [7], and as a high-stability frequency references [8], [9].one of the most challenging part in silicon MEMS oscillators is achieving a highly stable output and it results from the large native temperature coefficient of frequency (TCf) of silicon. TCf is the rate of frequency changing with temperature respect to a reference frequency. A TCf of silicon resonators without any compensation is approximately -30 ppm/ºC, which happens mostly because of the material softening of silicon. Compensation techniques for TCf reduction in silicon resonators have been described in [10-12], and can be classified as passive or active. Passive techniques need a layer of silicon dioxide which has positive TCf, for counteracting the negative silicon TCf. This method is effective but requires some process steps [13].Active techniques include ovenization [10] and electrostatic tuning [11]. By using these methods, devices and circuit-level tuning are inevitable to achieve sub-ppm instability level required for temperature compensated and oven controlled crystal oscillator applications [14].

For dynamic tuning, the operating temperature of device should be monitored continuously in order to put the necessary frequency changing in the tolerance range. Accurate temperature measurement needs the sensor and temperature-sensitive frequency reference to be in very close proximity, since oscillator frequency can be measured with high accuracy; the temperature-sensitive resonating element is a good candidate to be used as a self-thermometer [7]. Although temperature tracking can be done by help of the TCf of a single resonance mode, using dual MEMS resonators can deliver high sensitivity based on thermometric beat frequency approach [15].this is achievable by measuring a linear combination of two resonance modes in a single devise which have different temperature coefficient of frequency. In this way TCf_b is used instead of TCf to track stress, mass, pressure and temperature and this is due to the fact that TCf_b is greater than TCf and is linear, so makes the measurement more accurate. Also the future calibration will be more convenient. [16-18].

In this paper a new geometry to build temperature sensor based on dual mode single crystal silicon resonator is proposed which uses beat frequency in order to achieve better temperature sensitivity and high temperature coefficient of beat frequency (TCf_b).

2. Dual-Mode MEMS RESONATOR STRUCTURE

As it is shown in Fig. 1, the presented dual mode resonator is a single crystal silicon elliptical ring with 20-µm-thickness, supporting by one beam that attaches to the ring at quasi-nodal point which has negligible displacement compared to other parts of the ring structure when the ring vibrates in its intended mode shapes.

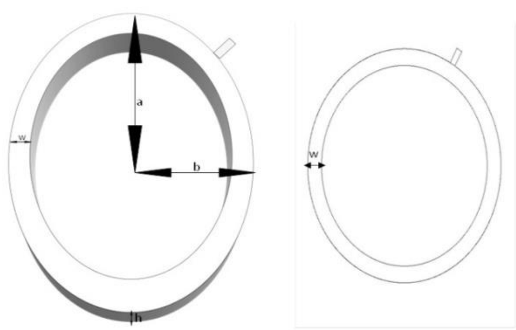


Fig. 1. Schematic of the proposed elliptical ring resonator

The proposed device can be excited in two special in-plane modes which resonant frequencies are very close together. As shown in Fig. 2, one of them has lateral displacement and the other one is the symmetric mode with mode number of 10.

3. PRINCIPLE OF OPERATION OF DUAL-MODE TEMPERTURE SENSING

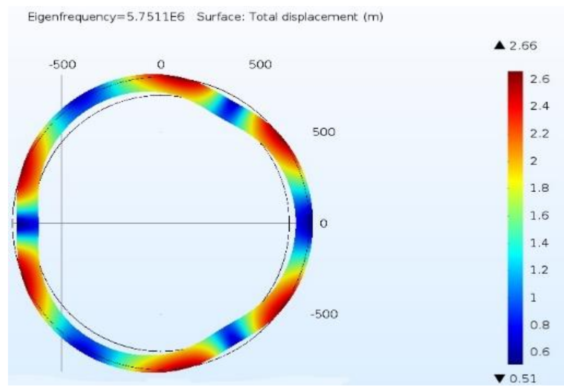
Dual mode temperature sensing can be defined as excitation of two resonance modes in a single device. In fact this issue led to both modes experience the same changes in ambient temperature [19]. The distinctive frequency-temperature specification of those two modes is used in order to compensate the reference frequency over temperature.

If the second mode is an a-order harmonic of the first mode, the beat frequency (f_b) is defined as a linear combination of f_1 and f_2 [19]:

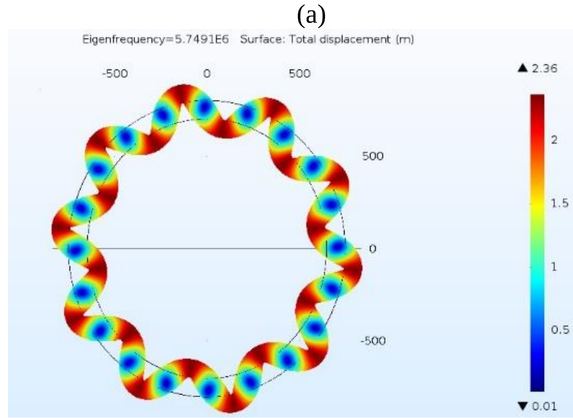
$$f_b = \alpha \cdot f_1 - f_2 \quad (1)$$

If these two modes occur very close together, the specific f_b values can be defined by controlling the distance between the first mode and second mode [7]:

$$f_b = f_1 - f_2 \quad (2)$$



(a)



(b)

Fig. 2. Two adjacent mode shapes of the proposed elliptical ring resonator simulated by COMSOL Multiphysics software. (a) First resonant mode. (b) Second resonant mode.

If the modes are close in frequency, f_1 and f_2 can directly mixed to generate f_b, so there is no need to integer/fractional frequency multipliers [20]. The TCf_0 value defines as the relative changes of resonance frequency with respect to temperature, can be expressed as:

$$TC^n f_0 = \frac{1 \partial^n f_0}{f_0 \partial T^n} \quad (3)$$

According to (2) and (3), DM temperature sensitivity is defined as:

$$TCf_b = \frac{f_1 \cdot TCf_1 - f_2 \cdot TCf_2}{f_b} \quad (4)$$

According to (4), one of the suggesting ways to enhance the temperature sensitivity is decreasing the beat frequency (f_b).because of the linear TCf_b of silicon; the TCf_b would also be a linear function of temperature. When f_b approaches a minimum (f_1=f_2), (4), can be approximated as follow:

$$TCf_b \cong \frac{f_2}{f_b}(TCf_1 - TCf_2) \quad (5)$$

Based on frequency ratio f_2/f_b, combination a large f_2 and small f_b, can improve the DM temperature sensitivity, further TCf_b improvement are achievable by maximizing ΔTCf (TCf_1-TCf_2).

4. TCF_B ENHANCEMENT BY BEAT FREQUNCY REDUCTION

Utilizing first mode and second mode for dual mode operation provide very small f_b by directly mixing two frequencies rather than utilizing fractional multiplication for obtaining a desired f_b. (f_b =f_1-f_2), [15].thus introducing additional complexity and noise to the system Fig. 3.

Semi-external major axis a=800µm, semi-external minor axis b=742µm, eccentricity ($e=\sqrt{1-(b/a)^2}$), e≈0.4 and ring width w=100µm correspond to the case that $f_1 \approx f_2$ or nearly zero f_b. Beat frequency between two intended modes was simulated in different dimensions while e and w are constant, Fig. 4. As it can be obtained from Fig. 4 in the designed elliptical ring resonator f_b is nearly zero. f_b is also simulated with different eccentricity in two different states wherein the e_1=e_2, it means that the elliptical ring is concentric and $e_1 \neq e_2$, So the elliptical ring is not concentric. For both simulations a=800µm and w=100µm, Fig. 5.

Temperature coefficient of frequency (TCf) for the mentioned frequency modes in single crystal silicon elliptical ring resonator was simulated accurately in COMSOL Multyphysics software. The extracted TCf_1 and TCf_2 while a=800µm, b=742µm, e=0.4, w=100µm and resonator thickness is 20µm are respectively 44ppm/ºC and 5.73 ppm/ºC. The resonator with frequency of 5.73 MHz and f_b of 2 kHz was designed by the methodology described.

According to (5), Combination of small f_b and large ΔTCf (TCf_1-TCf_2), provide enhanced DM temperature sensitivity Fig. 6, so in the proposed designed with very small f_b and almost large ΔTCf, the significant TCf_b can be accessible. The highest extracted TCf_b is 112231 ppm/ºC for a device with f_b=2 kHz Fig. 7, and nearly 75× larger than the previous DM measurements [7].

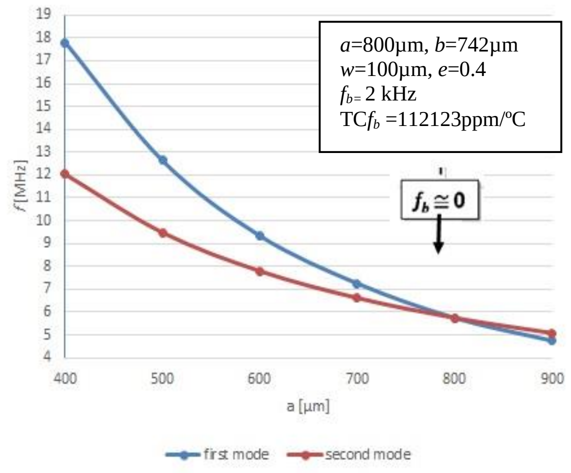


Fig. 3. Simulated frequency of f_1 and f_2 modes versus semi-external major axis (a) for an elliptical ring with w=100µm.

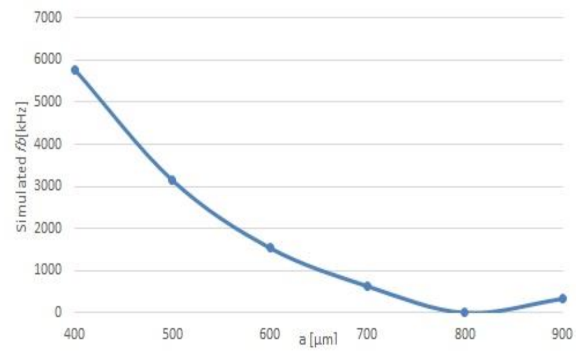


Fig. 4. Simulated f_b for resonator with w=100µm and e=0.4 and various a.

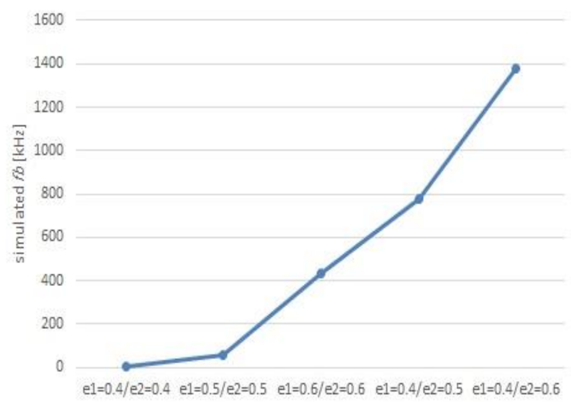


Fig. 5. Simulated fb versus e_1/e_2.

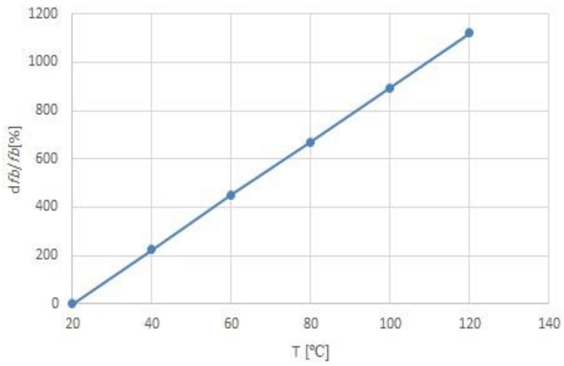


Fig. 6. Extracted TCf_b of DM resonator with f_b=2 kHz, simulated TCf_1=44ppm/ºC and TCf_2=5.73 ppm/ºC.

5. DUAL MODE EXCITATION FOR TEMPERATURE–STABLE BASED ON BEAT FREQUENCY

The DM resonator with these two frequency modes not only is applicable for high sensitivity thermometry, but also can be used as temperature-stable reference.

By zeroing the right–hand side of (4), the requirements for temperature -insensitive f_b in DM resonators are provided:

$$f_2 = f_1 \frac{TCf_1}{TCf_2} \tag{6}$$

Since f_1 and f_2 have nonzero TCf, f_b which is generated by mixing these two signals will remain constant over temperature. According to the (6), in DM resonators with known values of TCf_1 and TCf_2, must be designed to conditions in (6), f_2 /f_1 in temperature – intensive DM resonators determine the behavior (rather than f_2/f_b).

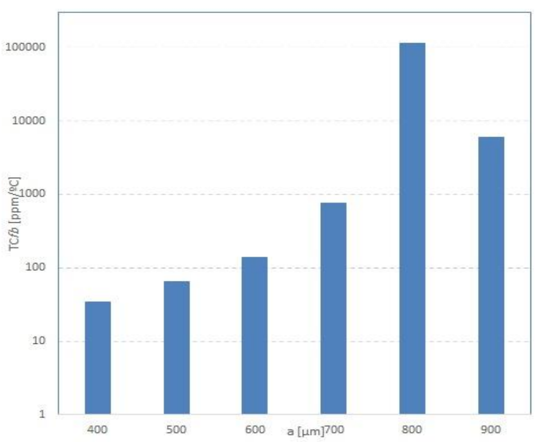


Fig. 7. Simulated TCf_b versus *a*.

6. CONCLUSION

In this paper, DM single crystal silicon elliptical ring resonator which can be used for temperature sensing was designed and optimized. This devise works based on beat frequency (f_b). For enhancing TCf_b, two frequency modes were excited simultaneously. These two modes were very close together, so the simulated fb was about 2 kHz. The reported device has TCf1 of about 44 ppm/ºC and TCf_2 of 5 ppm/ºC. Combination of small fb and large ΔTCf, present temperature coefficient of beat frequency (TCf_b) about 112000 ppm/ºC which leads to 75× improvement in TCf_b compared to previous demonstrated DM resonators.

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