CMOS-COMPATIBLE DUAL-RESONATOR MEMS TEMPERATURE SENSOR WITH MILLI-DEGREE ACCURACY

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Abstract: This paper presents a dual-resonator design which, not only enables temperature sensing of the resonators but also acts as a general-purpose temperature sensor. The frequency stability of the temperature compensated resonator depends on the accuracy with which the temperature of the resonator is measured. The dual-resonator design, described here, produces temperature-dependent beat frequency which is inherent to the resonator and thus eliminates any spatial and temporal thermal lag associated with the use of an external temperature sensor. Furthermore, this design can also be used as a CMOS-compatible digital temperature sensor. In this work, we achieved the sensor resolution of approximately 0.008°C which is comparable to that of the best CMOS temperature sensors available today.

Keywords: MEMS, Microresonator, Dual resonator, Beat frequency, Digital temperature sensor.

1. INTRODUCTION

The performance of many modern electronic devices depends on the accuracy and precision of the timing and frequency references they use. Temperature compensated low-power low-cost CMOS-compatible MEMS resonator-based oscillators are becoming an interesting and viable technology as a replacement for quartz crystals for timing and frequency reference applications [1]. An ideal thermometer for compensation of the temperature dependence of the resonator frequency, in MEMS would be one that is inherent in the resonator, such as the beat frequency method used in quartz crystal oscillators [2-4]. This method is superior to others, because the resonator itself is the temperature sensor – which is an advantage over any external thermometer.

In this paper, we present a dual-resonator design using composite Si-SiO_2 structures [5], which enable the application of the beat-frequency technique to MEMS resonator. The dual-resonator produces two similar frequencies with two different temperature sensitivities. By mixing these two frequency signals, a beat frequency can be generated which is a strong function of temperature. The resolution of the beat-frequency-thermometer is estimated to be approximately 0.008°C with an averaging time of one second.

2. DESIGN DESCRIPTION

A thermally coupled double-ended tuning fork (DETF) type dual-resonator, shown in Fig. 1, has two resonators with SiO_2 coated Si beams. The thickness of thermally grown SiO_2 coating is approximately 0.33 µm. The cross-section of the beams, shown in Fig. 1, is designed to achieve two different temperature coefficients of frequency (TCf) [5] for the two resonators, while keeping the two frequencies close together. These devices were fabricated using a CMOS-Compatible wafer scale encapsulation process [6]. The two frequencies, f_1 and f_2, from the dual resonator are mixed to form the difference frequency or beat frequency, f_{beat} as shown in Fig. 2. The temperature dependence of f_1, f_2 and f_{beat} can be expressed as:

$$f_1(T) = f_1(T_0) + a_1\Delta T + b_1\Delta T^2 + \dots \tag{1}$$

$$f_2(T) = f_2(T_0) + a_2\Delta T + b_2\Delta T^2 + \dots \tag{2}$$

$$f_{beat}(T) = f_{beat}(T_0) + (a_1 - a_2)\Delta T + \dots \tag{3}$$

where *a's* and *b's* are constants, T_0 is a reference temperature and $\Delta T = T - T_0$. The first order term of equation (3) is about 10,000X larger than the second order as well as all the other higher order

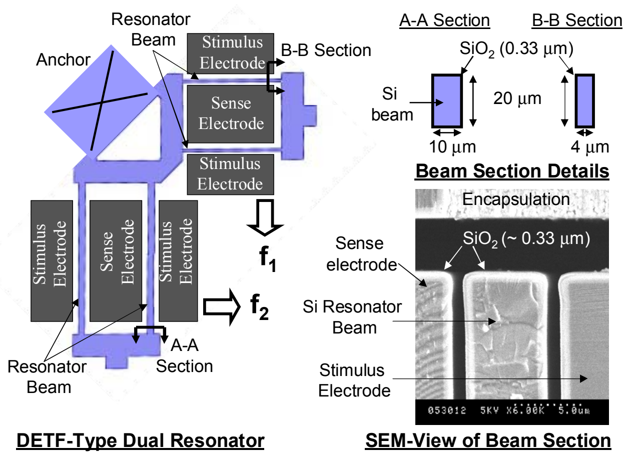

Fig. 1 Dual-resonator with composite beams of Si and SiO_2.

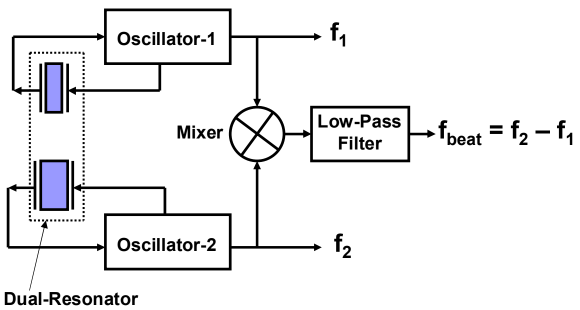

Fig. 2 Schematic of technique for generating the beat frequency.

terms for the temperature range of -40°C to 120°C. Therefore the fractional change in beat frequency after ignoring the higher order terms is given as,

$$\frac{\Delta f_{beat}(T)}{f_{beat}(T_0)} = \frac{(a_1 - a_2)\Delta T}{f_{beat}(T_0)} \qquad (4)$$

3. EXPERIMENTAL RESULTS

The resonator with frequency f_1 (~1.4 MHz) is first-order-temperature-compensated over the temperature range using an oxide layer for stiffness compensation [5], while the resonator with frequency f_2 (~1.5 MHz) has a larger TCf of -17ppm/°C as shown in Fig. 3. The difference in TCf arises from the different beam thicknesses for the two resonators. Since the frequencies of the dual-resonator are close together, the beat frequency f_{beat} is smaller and more sensitive to the

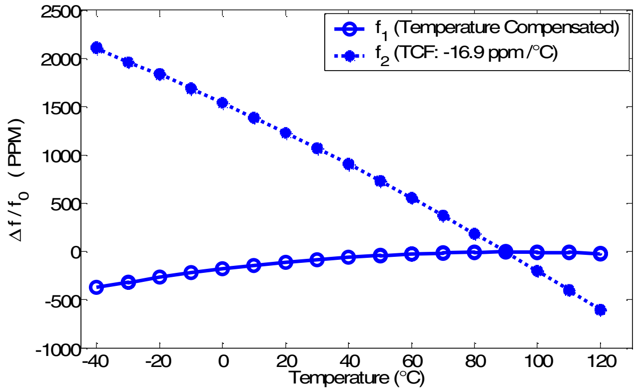

Fig. 3 Temperature dependence of f_1 and f_2 of dual-resonator.

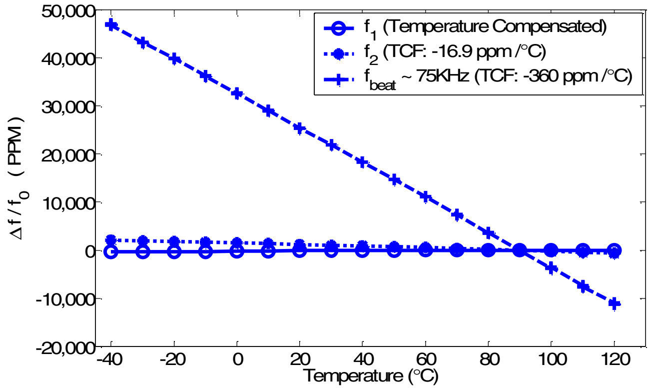

Fig. 4 Comparison of the temperature dependence of the beat frequency with that of the dual-resonator frequencies.

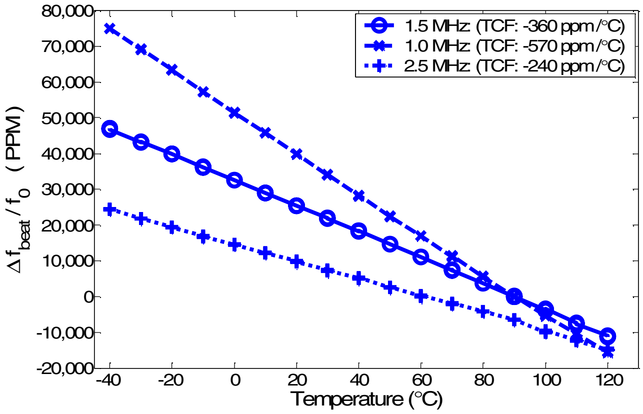

Fig. 5 Temperature dependence of f_{beat} for various designs having resonator frequencies in the range of 1.0MHz, 1.5MHz and 2.5MHz.

temperature changes, as shown in Fig. 4, with the TCf of - 360 ppm/°C. The high sensitivity as well as the linearity of f_{beat} has been verified on several devices as shown in Fig 5.

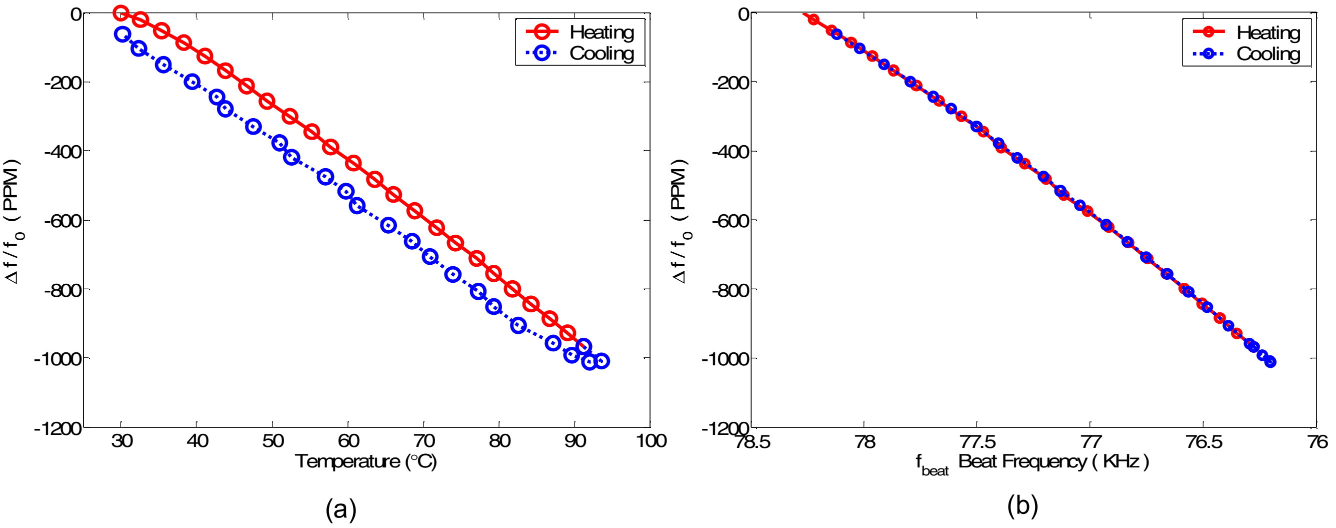

Fig. 6 Resonator f-T characteristic in rapid-temperature cycling (slew rate ~ 6°C /min) using (a) an external temperature sensor – Pt. RTD (b) beat frequency as a temperature sensor.

A significant advantage of the beat frequency technique is illustrated in Fig 6. During a rapid-temperature cycling (~ 6°C /min) from 30°C to 100°C to 30°C, a measurement of f versus T shows a large hysteresis due to thermal lag between the external temperature sensor (Pt. RTD) and the resonator - Fig 6(a). The f versus f_{beat} characteristics shows no hysteresis on the same scale - Fig. 6(b), because there is no physical separation between the thermometer and the resonator.

To compute the resolution of the beat-frequency temperature sensor it is important to be able to distinguish errors in temperature measurement from random variations in the true temperature of the measurement environment. To make this measurement, two different complete devices, with the same design, were simultaneously measured side-by-side in the same oven. Measurements of f_{beat} of both the devices were taken over a period of 10 hours. As can be seen in Fig. 7, there are large variations in the measurement results, but most of the variations are detected by both thermometers, indicating that these are true temperature variations. The uncorrelated variation is an indication of the errors in the beat-frequency thermometer. The correlation coefficient [7-9] of the two measurements x and y can be given as

$$\rho_{xy} = \frac{C_{xy}}{\sqrt{C_{xx}C_{yy}}} \qquad (5)$$

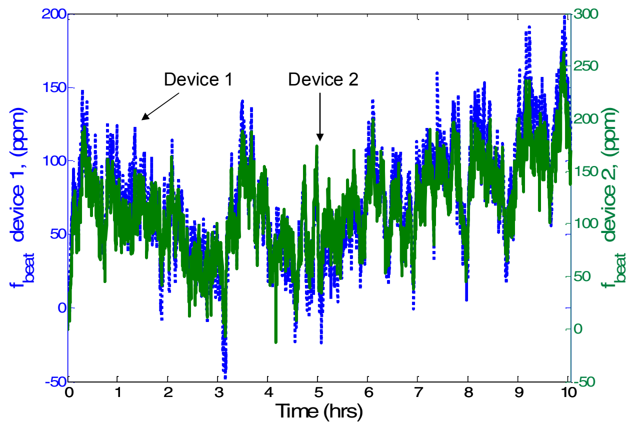

Fig. 7 Time-history plot of the beat frequencies (correlation coefficient ~ 0.9) from the two different devices at constant temperature (TCf of f_{beat} ~ -360 ppm/°C).

where C_{xy} is the co-variance between x and y, C_{xx} and C_{yy} is the variance of x and y respectively. Assuming that the resonator frequency is only affected by the temperature inside the oven and the temperature sensitivities of both the beat frequencies are same, the inherent noise of the temperature dependent beat frequency can be estimated by equation (6), [7-9].

$$\sigma_{nn} \approx \sqrt{C_{xx}(1-\rho_{xy})} \qquad (6)$$

where σ_{nn} is the noise in the measurement. It is also assumed that the noise component is approximately same in both the measurements.

Since the resonator based oscillators can have various types of noise other than white noise, we have used an IEEE recommended Allan variance [10] to calculate the variance in the measurements. The classical variance for such measurements depends on the number of data points and hence may not converge [10]. However, if the oscillator exhibits only white noise then the Allan variance and the classical variance should give the same result. The Allan variance for the above beat frequency measurement (C_{xx}) is estimated to be approximately 84 ppm^2 with an averaging time of 1.0 second. The correlation coefficient of the two beat frequencies is calculated to be 0.9. By computing the noise component (σ_{nn}) from equations (5) & (6) and using the temperature sensitivity of the beat frequency (Fig. 4.), the resolution of the dual-resonator beat-frequency-thermometer is evaluated to be approximately 0.008°C with an averaging time of one second.

4. CONCLUSIONS

The beat-frequency thermometer is probably the best temperature sensing technique for temperature compensation or temperature control of a MEMS-based reference oscillator. This technique eliminates the effect of thermal lag and static temperature gradients as the temperature signal comes directly from the resonator, and it provides a method that does not rely on analog signal processing, which might bring in added temperature coefficients. It is also important to point out that this device is a potentially interesting CMOS-Compatible digital thermometer for ordinary circuit applications. By using the compensated resonator to count the beat-frequency, the temperature can be determined to milli-degree accuracy, which makes this device competitive with the best CMOS thermometers available today.

5. ACKNOWLEDGMENTS

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