A 9.4 MHz, 0.011 mm², 107.6 ppm/°C single-port RC oscillator with temperature compensation

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Abstract. A 9.4 MHz single-port RC oscillator is introduced using 0.18 μm CMOS technology, which can be applied in cryogenic medical instruments. By combining a comparator with negative resistors and optimizing temperature coefficients of composite resistors, we are able to reduce the sensitivity of frequency to temperature. The proposed oscillator improves the stability of the frequency without significant increase in area, occupying only 0.011 mm². The measured frequency variation is less than ±0.5% from -65°C to 25°C and ±0.35% from 3.8V to 4.2V.

1. Introduction
Stable clock reference circuits are basic components of digital and mixed-signal circuits in microelectronics. In recent years, cryosurgical instruments have been rapidly developed for use in cancer treatment. A cryoprobe is sent to a specific organ in the body, removing tumour at a temperature ranging from 0°C to -60°C, making size and stability in frequency critical factors of operation. Though crystal oscillators have good performances, they are costly and cannot be integrated into a monolithic chip [1-2]. RC oscillators are more suitable as on-chip clock generators for these applications. Reducing core area and minimizing frequency sensitivity to temperature are the two main challenges for designing RC oscillators.

Several integrated oscillators with low temperature coefficient have been proposed in recent publications. Some designs adopt a feedback loop to compensate variations, utilizing frequency-to-voltage converters [3-4] or an integrated error feedback [5] to minimize their sensitivity to temperature variations. Others add a D/A converter based on frequency-to-current conversion to form a feedback loop [1]. Another method replicates certain part of the circuit to cancel non-idealities of the oscillator [6]. Nearly all of those works add other circuit modules to decrease frequency variation within a temperature range. Therefore the complexity and core area of the overall circuit have increased.

To solve the challenges mentioned above, a single-port RC oscillator is presented in this paper which focuses on reducing core area and optimizing frequency stability at low temperature [7]. We combine a comparator with negative resistors to offset temperature effects on transconductance. Meanwhile, the temperature coefficient of oscillation frequency is further reduced by optimizing the composite resistors. The article has four sections. Section II introduces the circuit configuration and optimization. Measurement results are presented in Section III. Finally, conclusions are shown in Section IV.
2. Circuit Configuration

2.1. Overview of the operation

The overall circuit is composed of a main oscillation circuit and inverters. The main oscillation circuit consists of charging and discharging circuit, a comparator and negative resistors produced by transistors. The inverter plays the role of shaping the original signal.

Figure 1 shows the oscillator circuit. $R_1$ represents a positive resistor which is in parallel to negative resistors $R_2$ and $R_3$. The process of oscillation occurs periodically. $U_C$ represents the varying voltage on the capacitor $C_1$ and $V_{OUT}$ represents the voltage sending back to the inverter. The comparator is used for comparing $U_C$ with threshold voltage $V_{TH}$, which consists of only two CMOS transistors in this work. When $U_C$ is relatively small, the transistor $T_1$ is turned on and $T_2$ is turned off. Then $V_{OUT}$ will decrease and the capacitor $C_1$ is at the state of charging. When $U_C$ is relatively large, the transistor $T_2$ is turned on and $T_1$ is turned off. After that $V_{OUT}$ will increase and the capacitor $C_1$ is at the state of discharging. As the capacitor $C_1$ charges and discharges, the output voltage changes cyclically.

![Figure 1. Schematic of the single port oscillator.](image1)

![Figure 2. A typical negative resistor circuit [8].](image2)

2.2. Negative resistor

A resistor is usually positive, which means higher voltage leads to larger current. A negative resistor, however, passes through smaller current when voltage is higher. A simple way to make negative resistor is to combine a source follower with positive feedback as shown in Figure 2 [8]. If channel length effect and body effect are neglected, the following resistor value calculation equation holds:

$$R_{in} = -\frac{1}{g_{m1}} - \frac{1}{g_{m2}}$$

(1)

Both the negative resistors $R_2$ and $R_3$ in Figure 1 are generated by two CMOS transistors as shown in Figure 2. The capacitor voltage $U_C$ also functions as the bias voltage supplied to $R_2$ and $R_3$. We combine the comparator and negative resistors to improve the oscillation frequency stability. The oscillator in Figure 1 is composed of only eight CMOS transistors, a resistor and a capacitor.

A single port oscillator with a positive resistor, a negative resistor, a capacitor and an inductor has been presented in [8]. The greatest advantage of this structure is its simplicity. However, the oscillation frequency is significantly affected by the positive resistor and the transconductance of the negative resistor at low temperature. A method of overcoming those drawbacks will be further explained in the following sections.

2.3. Oscillation frequency

By analyzing the circuit in Figure 1, the following equation is obvious:

$$U_C + R_1 C_1 \frac{du_C}{dt} = V_{OUT}$$

(2)

The charging time $t_1$ and the discharging time $t_2$ can be calculated as following:
The overall expression of oscillator frequency is

\[ f = \frac{1}{t_1 + t_2} \]

Figure 3 shows the waveforms of capacitor voltage and output voltage. When the capacitor is being charged, the oscillator outputs high level, while the output is low during the capacitor is discharging. The duty cycle is determined by \( t_1/(t_1 + t_2) \), which can be controlled by configuring the circuit parameters.

Combined with Figure 1 and Figure 2, the comparator provides the negative resistors with the current. And both the comparator and the negative resistors are composed of CMOS transistors. Therefore the effect of transconductance \( g_m \) variations on oscillation frequency is offset with temperature changes in the Expression (3), (4). Then the threshold voltage \( V_{TH} \) and the resistor \( R_1 \) are two major variables affected by temperature. The next section mainly discusses the method of temperature compensation for the two variables.

\[ t_1 = -R_1 C_1 \ln \left( \frac{V_{TH1}}{V_{DD}/2 - (V_{DD} - |V_{TH1}|) |g_m R_2|} \right) \]  \hspace{1cm} (3)

\[ t_2 = -R_1 C_1 \ln \left( \frac{V_{TH2}}{V_{DD}/2 - (V_{DD}/2) |g_m R_3|} \right) \]  \hspace{1cm} (4)

The overall expression of oscillator frequency is

\[ f = \frac{1}{t_1 + t_2} \]  \hspace{1cm} (5)

2.4. Temperature coefficient compensation

In this work, the temperature coefficient of the capacitor and the second order temperature coefficient of the resistor is neglected since they are rather small. The expressions of temperature dependent parameters \( V_{TH} \) and \( R_1 \) are shown as follows:

\[ |V_{TH}| = |V_{TH}|(1 + \alpha_{VT}(T - 25)) \]  \hspace{1cm} (6)

\[ R_1 = R_1(1 + \beta_{RT}(T - 25)) \]  \hspace{1cm} (7)

where \( \alpha_{VT} \) and \( \beta_{RT} \) represent the temperature coefficient of the threshold voltage \( V_{TH} \) and the resistor \( R_1 \) respectively. Then the relationship between charging and discharging time and temperature could be written as:

\[ t_1 \approx t_2 \propto R_1 C_1 (1 + \beta_{RT}(T - 25)) \cdot \ln(|V_{TH}|(1 + \alpha_{VT}(T - 25))) \]  \hspace{1cm} (8)

Combining the Equations (1), (3), (4), (5), (8), the equations of frequency versus other variables are expressed as (9) and (10). \( K \) represents the overall temperature coefficient which is needs to be optimized in the following step.

\[ f \propto 1/(2R_1 C_1 K) \]  \hspace{1cm} (9)

\[ K = (1 + \beta_{RT}(T - 25)) \ln(|V_{TH}|(1 + \alpha_{VT}(T - 25))) \]  \hspace{1cm} (10)

For a certain process, the value of \( \alpha_{VT} \) has been determined. Selecting a suitable \( \beta_{RT} \) can minimize the sensitivities of the frequency to temperature. Composite resistors with zero temperature coefficient are often used to compensate first order temperature coefficient in most circuit implementations [5]. However, in this design, the value of \( \beta_{RT} \) is used to compensate the variations of the threshold voltage \( V_{TH} \) and the resistor \( R_1 \) with temperature. Through parameter sweep in the designing program, the corresponding value of \( \beta_{RT} \) can be obtained with a
minimum change of $K$ from -65°C to 25°C. Regard the composite resistors and the threshold voltage $V_{TH}$ as a whole to maximize temperature compensation.

As shown in Figure 4, the red line denotes the original $K$ variation when the resistor $R_1$ adopts only one type ($\beta_{RT} = 3.05 \times 10^{-3} \Omega/\degree C$). And the black line denotes the optimized curve when the resistor $R_1$ adopts two different types ($\beta_{RT} = -8.535 \times 10^{-4} \Omega/\degree C$). Obviously, difference between maximum and minimum of $K$ is reduced from 4.241 to 0.011. The optimization is validated by simulation in Cadence. The value of $\beta_{RT}$ is determined by resistors with positive and negative temperature coefficient. Figure 5 shows different types of resistors can have a significant impact on the overall frequency sensitivity from -65°C to 25°C. In the original design, the overall frequency variation is ±5.17%. The optimized composite resistors have a better performance than ideal resistors, which further reduce the frequency variation from ±0.85% to ±0.41% within the same temperature range.

With the above optimization method, the core area of the oscillator is rarely increased, and the frequency stability is greatly improved. This method can be used to optimize oscillator frequency variations in any temperature range.

![Figure 4. The overall $K$ variations from -65°C to 25°C with different values of $\beta_{RT}$.](image)

![Figure 5. Simulated frequency variations from -65°C to 25°C with different composite resistors.](image)

3. Experimental results
The proposed oscillator is fabricated in standard 0.18 μm CMOS process with 5V IO. This oscillator is applied for cryogenic medical instruments which mainly work in subzero temperature [9]. Therefore, the optimized temperature range for this design is from -65°C to 25°C. Figure 6 shows the die photograph with a core area of 0.011 mm², where the capacitor accounts for more than half of the area. Figure 7 shows the stable waveform measured by Tektronix MDO3034 oscilloscope at room temperature. Its cycle jitter is 0.10% calculated as standard deviation/period which is measured by the oscilloscope. The average frequency is 9.39MHz at a supply voltage 4V. Figure 8 shows the frequency variation is ±0.5% and temperature coefficient is 107.6 ppm in the temperature range of -65°C to 25°C. Figure 9 shows the frequency variation is ±0.35% in the supply voltage range from 3.8V to 4.2V. Experimental results are consistent with the simulation results shown in Figure 5.
Table 1 summarizes the performance of this design and other CMOS oscillators published in recent years. The oscillator in this paper exhibits a competitive advantage, featuring a small area and a good frequency stability. This work is useful for on-chip reference clocks of cryogenic applications.

**Figure 6.** Die micrograph of the oscillator.

**Figure 7.** Waveform of the oscillator at room temperature.

**Figure 8.** Measured frequency variation from -65°C to 25°C.

**Figure 9.** Measured frequency variation from 3.8V to 4.2V at room temperature.

**Table 1.** Performances summary and comparison.

|                  | [1] | [2] | [3] | [4] | [6] | [9] | [10] | This Work |
|------------------|-----|-----|-----|-----|-----|-----|------|----------|
| **CMOS Technology** | 0.35μm | 0.35μm | 0.18μm | 0.18μm | 0.35μm | 0.18μm | 0.18μm | **0.18μm** |
| **Measurement Approach** | Experiment | Experiment | Experiment | Simulation | Experimen | Simulation | Simulation | Experiment |
| **Frequency [MHz]** | 30 | 4 | 10 | 3.82 | 1 | 1.92 | 6.27 | **9.4** |
| **Supply Voltage [V]** | 3 | 3 | 1 | 1.2 | 3.3 | 0.9 | 1.8 | **4** |
| **Temp. Coeff. [ppm/°C]** | 90@-20~100°C | 53.9@-30~120°C | 67@-20~120°C | 135@-20~80°C | 24.24@-40~125°C | 121@-40~85°C | 22.3@-20~75°C | **107.6@-65~25°C** |
| **Freq. Variation with Supply [%/V]** | - | 0.6@2.4~4V | <0.05@1.2~3V | - | 0.28@<3~4.5V | 0.33@0.9~2V | - | **≥0.35@3.8~4.2V** |
| **Area [mm²]** | 0.08 | 0.05 | 0.22 | 0.09 | 0.04 | 0.037 | - | **0.011** |
4. Conclusions
In this work, a capacitor, compositred resistors, a comparator and negative resistors constitute a simple oscillator. Combining a comparator with negative resistors is designed to offset temperature effects on transconductance $g_m$. And optimizing composite resistors with positive and negative temperature coefficients is used to compensate the overall first order temperature coefficients of the resistors and threshold voltage $V_{TH}$. The frequency stability is improved to 107.6 ppm in the temperature range from -65°C to 25°C. The fabricated circuit occupies $0.011 \text{ mm}^2$, a much smaller area compared to most of the state-of-the-art designs for temperature compensated on-chip oscillators.

The proposed oscillator works stably at low temperatures under the supply voltage. It is mainly applied in cryogenic medical instruments. This design makes a good balance between area and frequency stability.

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