# *Low-Voltage Low-Power CMOS Oscillator with Low Temperature and Process Sensitivity*

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# Low-Voltage Low-Power CMOS Oscillator with Low Temperature and Process Sensitivity

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***Abstract*— The design of an on-chip RC-based oscillator, implemented in a standard 0.35 µm CMOS process, without any external component, is presented. The proposed oscillator provides a clock signal at a frequency of about 80 KHz with a temperature coefficient smaller than 842 ppm/°C over a temperature range from 0 to 80 °C and a standard deviation due to process variations smaller than 4%, without any external trimming. The proposed oscillator operates with a supply voltage of 1 V and has a power consumption of about 1 µW at room temperature. The chip area is 0.24 mm².**

## I. INTRODUCTION

The proliferation of mobile and pervasive electronic equipment is a major motivation for the design of low voltage and low power circuits, both digital and analog, that would reduce the need for battery replacement or recharging, allow lighter batteries to be used or larger communication distance, depending on the application. Moreover, since the supply voltage allowed in sub-micron process technologies is decreasing, analog circuits must be able to operate with a supply voltage as low as 1 V.

RC oscillators are often used in micro controller, biomedical or other ASIC applications where the accuracy is not very important (1 to 10%) and the frequency is quite low. Indeed, the accuracy of the oscillation frequency is affected by the accuracy of the resistor and capacitor used to determine the frequency. Several implementations can be found in the literature [1-4]. RC oscillators are cheaper than crystal oscillators and do not require inductors. Since in digital CMOS processes the tolerance on the value of resistors is larger than 30%, most of the RC oscillators presented in the literature use an external resistor [2-4], which can have accuracy smaller than 1%, allowing a frequency accuracy of few percents. In this paper, we present an oscillator without any external component and trimming, capable of 1 V supply voltage. Such oscillator is aimed to be used as a clock circuit in a passive microwave RFID transponder where an accuracy smaller than 15% is acceptable but a µW power consumption is required to achieve operating range larger than several meters [5].

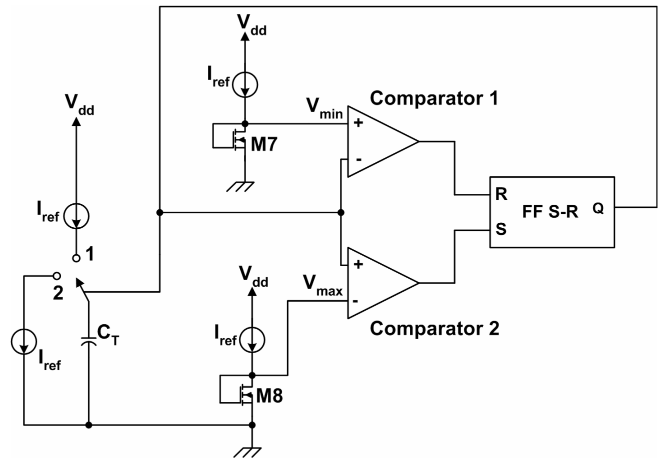


Fig. 1: Block diagram of the proposed oscillator.

## II. CIRCUIT DESCRIPTION

The block diagram of the proposed oscillator is shown in Fig. 1. It consists of a current generator circuit that provides a reference current $I_{ref}$, used to charge and discharge a capacitor $C_T$, and two comparators that compare the voltage across such capacitor with two threshold voltages $V_{min}$ and $V_{max}$; the output voltages of the two comparators are then used, through an SR-flip flop, to drive the input switch. When the voltage across the capacitor becomes larger than $V_{max}$, the output of the comparator 2 goes high, the flip flop is set, the switch goes to position 2 and the capacitor is discharged. When the voltage across the capacitor becomes smaller than $V_{min}$, the output of the comparator 1 goes high, the flip flop is reset, the switch goes to position 1 and the capacitor is charged. The oscillation frequency has the expression:

$$f = \frac{I_{REF}}{2\,C_T\,(V_{\max} - V_{\min})}\,, \quad (1)$$

where the meaning of all parameters is illustrated in Fig. 1. Both $V_{min}$ and $V_{max}$ are given by the gate-source voltage of a diode-connected MOS transistor biased by the reference current. The I-V characteristic of a MOS in the saturation region can be approximated by

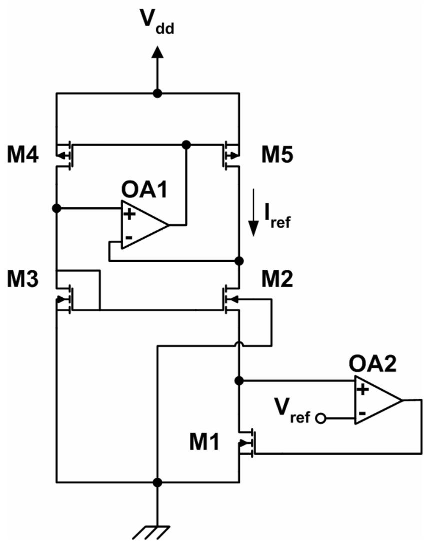


Fig. 2: Schematic of the current reference generator.

$$I_D = \frac{\mu C_{ox}}{2}\frac{W}{L}\left(V_{GS} - V_{th}\right)^2 = \frac{k}{2}\left(V_{GS} - V_{th}\right)^2, \qquad (2)$$

where $\mu$ is the carrier mobility in the channel, $V_{th}$ is the threshold voltage, $W$ and $L$ are the channel width and length, respectively. As a consequence, by using (2), the oscillation frequency can be written as:

$$f = \frac{\sqrt{I_{REF}}}{2\,C_T\sqrt{2/k_8}\left(1-M\right)}, \qquad (3)$$

where $M = \sqrt{k_8/k_7}$. Since the mobility has a negative temperature coefficient, in order to achieve a low sensitivity to temperature variations, the reference current must have a positive temperature coefficient. The sensitivity of the oscillation frequency to process variations depends on the accuracy of the capacitor, on the variation of the mobility and of the reference current.

The most critical issue in the design of the proposed oscillator is the generation of the reference current, which must have a small sensitivity to process variations and must be small in order to keep the power consumption as small as possible. The parasitic circuit elements and the intrinsic delays of the comparators and of the SR-flip flop are negligible because the oscillation frequency is quite low.

*A. Current Reference Generator*

The schematic of the current reference is shown in Fig. 2. Transistors M2 and M3 operate in the subthreshold region. The I-V characteristic of a MOS in the subthreshold region can be well approximated by

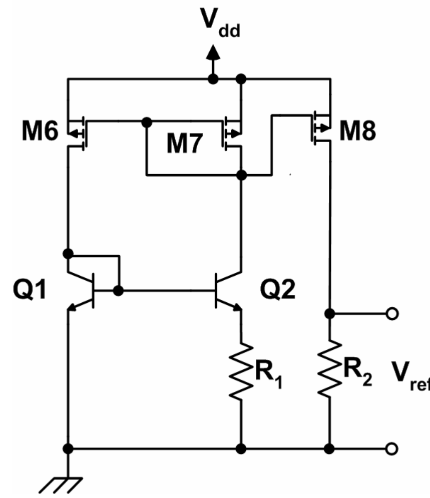


Fig. 3: Schematic of the voltage reference generator.

$$I_D = \mu V_T^2 \frac{W}{L}\exp\left(\frac{V_{GS}-V_{th}}{mV_T}\right)\left[1-\exp\left(-\frac{V_{DS}}{V_T}\right)\right], \qquad (4)$$

where $V_T$ is the thermal voltage and $m$ is the subthreshold slope parameter. The op-amp OA1 enforces the same voltage on the drain of M4 and M5 in order to impose equal currents in the two branches of the current reference generator. The op-amp OA2 sets the drain voltage of M1 to the reference voltage $V_{ref}$. The generated current has the expression:

$$I_{ref} = \frac{k_3}{2\left(1-N\right)^2}V_{ref}^2, \qquad (5)$$

where $N = \sqrt{k_3/k_2}$. In order to achieve a reference current with a positive temperature coefficient, as required for the temperature compensation of the oscillation frequency, the temperature coefficient of the reference voltage must be positive. Moreover, in order to minimize the sensitivity to process variations, the reference voltage must only depend on ratios of parameters so that it is just affected by matching errors.

*B. Voltage Reference*

The schematic of the voltage reference circuit is shown in Fig. 3. By assuming that the currents in the three branches of the circuit of Fig. 3 are identical, the voltage reference reads

$$V_{ref} = \frac{R_2}{R_1}V_T\ln\left(n\right), \qquad (6)$$

where $n$ is the ratio of the emitter area of Q1 to the emitter area of Q2. As clear from (6), the reference voltage has a positive temperature coefficient and, when considering the process variations, it is only affected by matching errors.

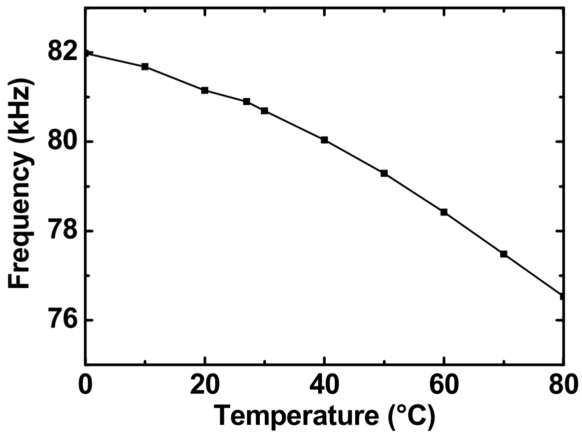


Fig. 5: Oscillation frequency of the proposed circuit vs. temperature.

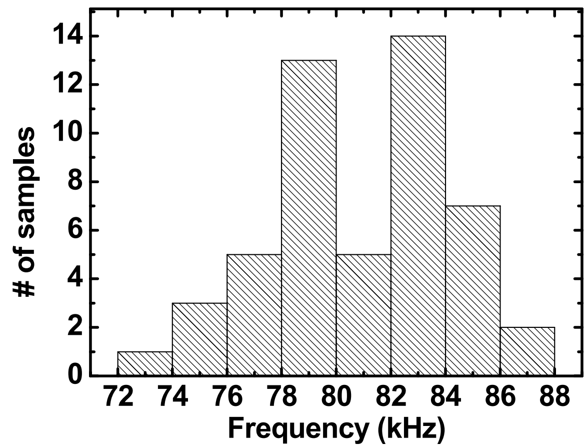


Fig. 6: Histogram of the oscillation frequency for 50 runs of the Montecarlo simulation.

## III. TEMPERATURE COEFFICIENT

As a first approximation we can assume that the mobility has a temperature dependence given by [6],

$$\mu = \mu_0 \left( \frac{T}{T_0} \right)^{\mu_T}, \tag{7}$$

where $\mu_0$ is the mobility at the reference temperature $T_0$, $\mu_T$ is exponent mobility coefficient. By differentiating (3) and taking into account (5) and (6), we can derive the temperature coefficient of the oscillation frequency:

$$\frac{\partial f}{\partial T}\frac{1}{f} = \frac{\partial V_{ref}}{\partial T}\frac{1}{V_{ref}} + \frac{1}{2}\left( \frac{\partial \mu_3}{\partial T}\frac{1}{\mu_3} + \frac{\partial \mu_8}{\partial T}\frac{1}{\mu_8} \right) = \frac{\partial V_{ref}}{\partial T}\frac{1}{V_{ref}} + \frac{\mu_T}{T}. \tag{8}$$

By differentiating (6) with respect to the temperature, we obtain

$$\frac{\partial V_{ref}}{\partial T}\frac{1}{V_{ref}} = \frac{1}{T}. \tag{9}$$

As a consequence, the relative temperature coefficient of the oscillation frequency is

$$\frac{\partial f}{\partial T}\frac{1}{f} = \frac{1}{T}(\mu_T + 1). \tag{10}$$

Since in our IC technology, the exponent mobility coefficient is -1.3, a theoretical temperature coefficient of about 1000 ppm/°C can be achieved, at room temperature.

## IV. PROCESS VARIATIONS SENSITIVITY

From (3), (5) and (6) we can derive the following expression of the oscillation frequency,

$$f = \frac{\sqrt{k_3 k_8}}{2\, C_T \sqrt{2}(1-M)(1-N)} V_{ref}. \tag{11}$$

If the matching errors are neglected, $V_{ref}$, $M$ and $N$ in (11) can be considered process independent, since $M$ and $N$ are $W/L$ ratios and $V_{ref}$ is generated from the supply voltage through a partition coefficient $\alpha$ ($V_{ref} = \alpha V_{dd}$), which is only affected by matching errors. Therefore, the sensitivity of the oscillation frequency to process variations is due to the carrier mobility $\mu$ and to the accuracy of the capacitor $C_T$. To first order, from (11), we have:

$$\frac{df}{f} = \frac{d\mu}{\mu} - \frac{dC_T}{C_T}, \tag{12}$$

In a standard RC-oscillator, the standard deviation of the oscillation frequency depends on the accuracy of the resistor and the capacitor that determine the oscillation frequency. In the proposed oscillator, instead, as is clear from (12), the standard deviation of the oscillation frequency depends on the accuracy of a capacitor and of the mobility, which has a standard deviation much smaller than that of a resistor. Such solution allows us to implement the proposed oscillator in a fully integrated way, without any external component, achieving, at the same time, an accuracy good enough for a broad range of applications.

## V. SIMULATION RESULTS

The proposed current reference circuit has been implemented in AMS 0.35 µm CMOS. Simulations show that the proposed oscillator generates a clock signal at about 80 kHz. The proposed circuit operates with a supply voltage of 1 V and consumes a maximum power consumption, at 80 °C, of about 1.12 µW. The power consumption decreases to 1.04 µW, at 0 °C. Fig. 5 shows the oscillation frequency as function of the temperature. From simulation results we can derive that the proposed oscillator has a temperature coefficient of about

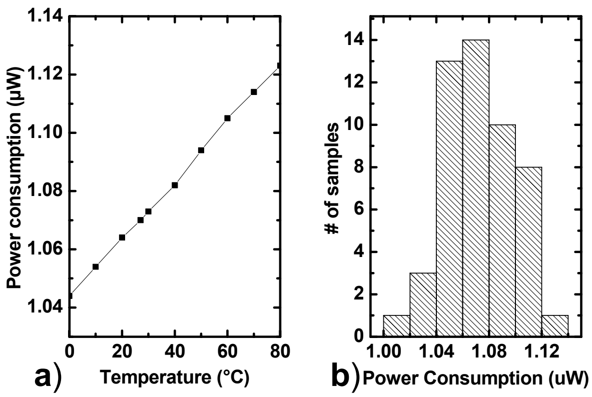


Fig. 7: a) Power consumption vs. temperature, b) Histogram of the power consumption for 50 runs of the Montecarlo simulation.

842 ppm/°C over a temperature range from 0 to 80 °C, which is in good agreement with the theoretical results provided by (10). When the supply voltage varies from 1 to 1.5 V, the oscillation frequency varies from 80 kHz to 79 kHz, leading to a line sensitivity of -2.5%/V.

In order to evaluate the sensitivity of the oscillation frequency to process variations, a Monte Carlo simulation has been performed and the results are shown in the histogram of Fig. 6. Simulation results show a mean value of the oscillation frequency of 80.85 kHz and a standard deviation of 3.19 kHz, leading to a 3σ of about 11.85%, which is good enough for many applications, such as the clock generator of passive microwave transponders, where an accuracy of 15% is typically acceptable, or in biomedical applications. Fig. 7a shows the variation of the power consumption as function of temperature. A Monte Carlo simulation has also been performed in order to evaluate the dispersion of power consumption due to process variations.

As is clear from Figs. 7a and 7b, power consumption is always smaller than 1.14 μW. The area occupation on the chip is 0.24 $mm^2$. The performance of the proposed oscillator is compared with those of other designs already reported in the literature in Table I. We can note that the proposed oscillator has the lowest power-to-frequency ratio (0.014 μW/kHz) and the lowest temperature coefficient. The sensitivity of the circuit to process variations is acceptable for several applications but larger than that of other circuits considered in Table I, all of which however have the drawback of requiring additional external components, contrary to our proposed solution.

Table I: Comparison with other results reported in the literature.

| | This work | Hwang [1] | Lasanen [2] | Bala [4] | Kakela [7] |
|---|---|---|---|---|---|
| Technology | 0.35 μm CMOS | 2 μm CMOS | 0.35 μm CMOS | 0.18 μm CMOS | 3 μm CMOS |
| Min Supply Voltage (V) | 1 | 2 | 1 | 1.25 | 2.5 |
| Frequency | 80 kHz | 0.3-100 Hz | 100kHz-7MHz | 6-24 MHz | 34.6 kHz |
| Max. power consumption | 1.14 μW | 0.3 μW | 52 μW | 1.12mW | 5.9 μW |
| Line sensitivity | -2.5%/V | N/A | 1.9%/V | N/A | -2.3%/V |
| TC | 842 ppm/°C | N/A | 1.4 %/V | N/A | -3%/V |
| Relative 3σ Frequency | 11.85% | N/A | 5% | 4% | 13% |
| Ext R, C | No | No | Yes | Yes | Yes |
| Area ($mm^2$) | 0.24 | 0.281 | 0.09 | 0.14 | 0.1 |

## VI. Conclusion

A low-frequency oscillator implemented in AMS 0.35 μm CMOS has been presented, which does not require any external component and can therefore be fully integrated. The proposed circuit is suitable for low power and low voltage applications in virtue of the supply voltage of 1 V and of a power consumption of about 1.1 μW. Power-to-frequency ratio and temperature sensitivity are significantly smaller than those obtained by comparable designs in the literature. The proposed oscillator can be used in applications where a dispersion (3σ) of frequency due to process variations slightly larger than 10% can be accepted, such as passive RFID transponders or biomedical applications.

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