Low-voltage nanopower clock generator for RFID applications

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Low-voltage nanopower clock generator for RFID applications

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ABSTRACT

The design of an on-chip RC-based oscillator, implemented in a standard 0.35 μm BiCMOS process, without any external component, is presented. The proposed oscillator provides a clock signal at a frequency of 50 kHz with a temperature coefficient smaller than 0.3%/°C over a temperature range from 0 to 80 °C, without any external trimming. The proposed oscillator operates with a supply voltage of 0.8 V and has a power consumption of 0.62 μW at room temperature. The chip area is 0.24 mm^2.

1. 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, allowing 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 of 1 V or less.

RC oscillators are often used in micro controller, biomedical or other ASIC applications where the accuracy is not very important (1–10%) 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 0.8 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].

2. 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

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

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 an MOS in the saturation region can be approximated by

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

where μ is the carrier mobility in the channel, V_{th} is the threshold voltage, W and L are the channel width and length, respectively.

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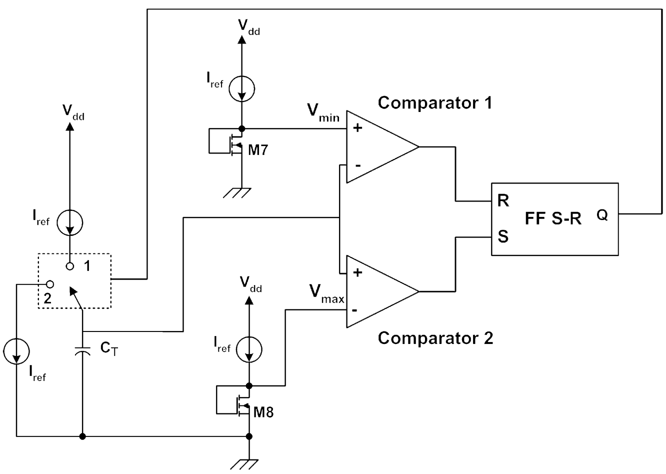

Fig. 1. Block diagram of the proposed oscillator.

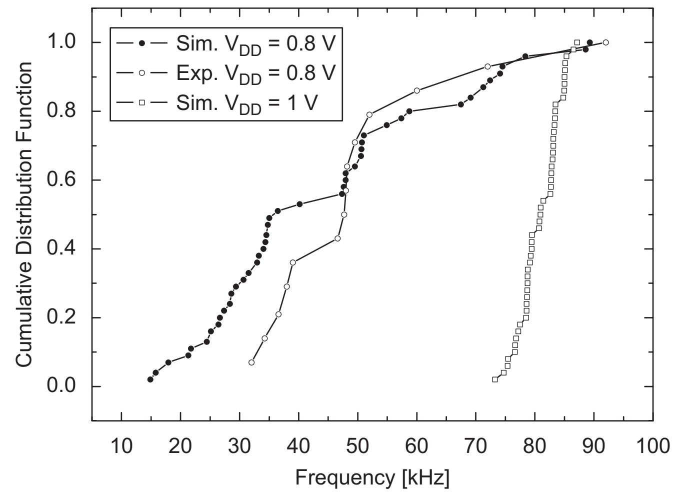

Fig. 4. Cumulative distributions of simulated and measured oscillator frequencies with supply voltage of 0.8 V.

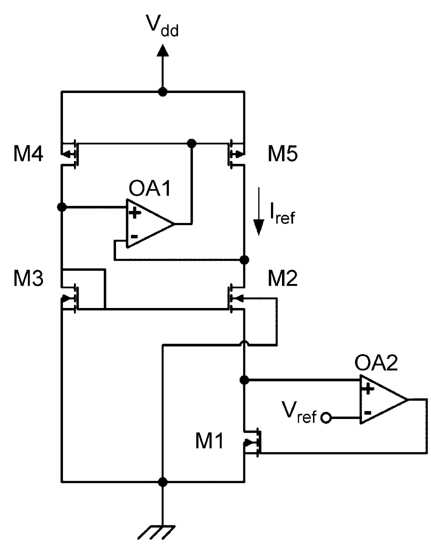

Fig. 2. Schematic of the current reference generator.

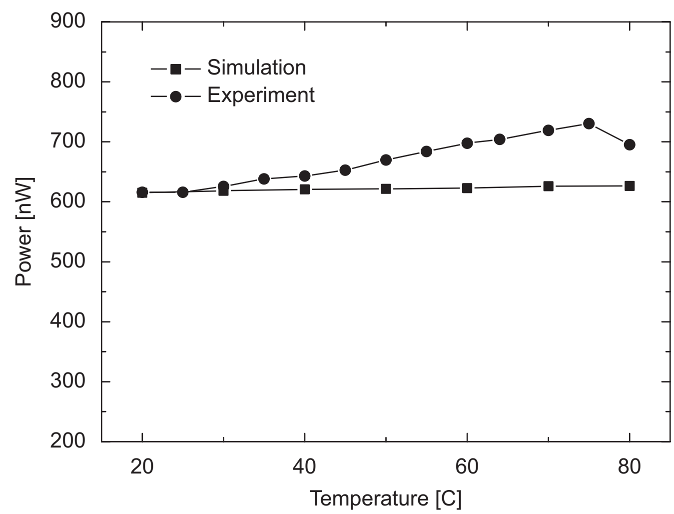

Fig. 5. Simulated and measured power consumption vs. temperature.

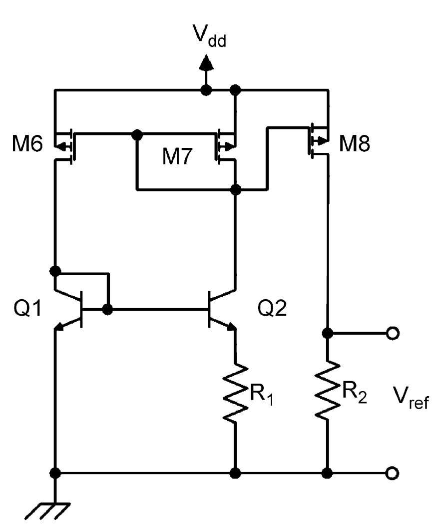

Fig. 3. Schematic of the voltage reference generator.

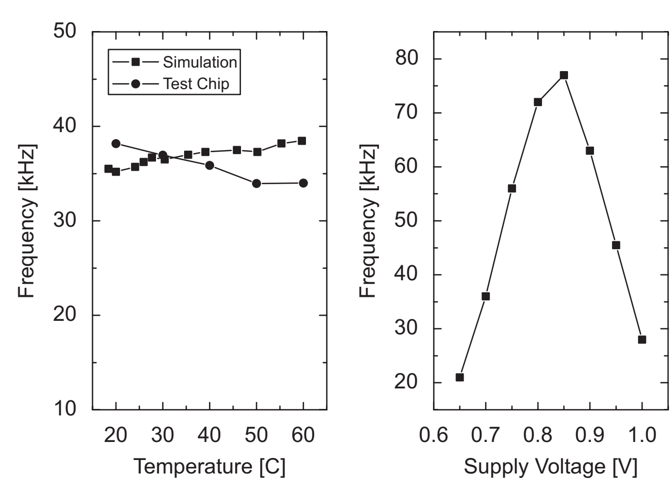

Fig. 6. Frequency vs. temperature (left); Frequency vs. power supply voltage (right).

Table 1
Comparison with other results reported in the literature

	This work	Hwang [1]	Lasanen [2]	Bala [4]	Kakela [7]
Technology (μm CMOS)	0.35	2	0.35	0.18	3
Min supply voltage (V)	0.8	2	1	1.25	2.5
Frequency	50 kHz	0.3–100 Hz	100 kHz–7 MHz	6–24 MHz	34.6 kHz
Max. power consumption	0.62 μW	0.3 μW	52 μW	1.12 mW	5.9 μW
TC	0.2%/°C	N/A	1.4 %/V	N/A	−3%/V
Ext R, C	No	No	Yes	Yes	Yes
Area (mm^2)	0.24	0.281	0.09	0.14	0.1

As a consequence, by using (2), the oscillation frequency can be written as:

$$f = \frac{\sqrt{I_{\text{ref}}}}{2C_T\sqrt{2/k_8}(1-M)}, \tag{3}$$

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.

2.1. Current reference generator

The schematic of the current reference is shown in Fig. 2.

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

$$I_{\text{ref}} = \frac{k_3}{2(1-N)^2}V_{\text{ref}}^2, \tag{4}$$

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.

2.2. 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

$$V_{\text{ref}} = \frac{R_2}{R_1}V_T\ln(n), \tag{5}$$

where n is the ratio of the emitter area of Q1 to the emitter area of Q2. As clear from (5), the reference voltage has a positive temperature coefficient and, when considering the process variations, it is only affected by matching errors.

3. Temperature coefficient

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

$$\mu = \mu_0\left(\frac{T}{T_0}\right)^{\mu_T}, \tag{6}$$

where μ_0 is the mobility at the reference temperature T_0, μ_T is exponent mobility coefficient. By differentiating (3) and taking into account (4) and (5), we can derive the temperature coefficient of the oscillation frequency:

$$\frac{\partial f}{\partial T}\frac{1}{f} = \frac{\partial V_{\text{ref}}}{\partial T}\frac{1}{V_{\text{ref}}} + \frac{1}{2}\left(\frac{\partial \mu_3}{\partial T}\frac{1}{\mu_3} + \frac{\partial \mu_8}{\partial T}\frac{1}{\mu_8}\right) = \frac{\partial V_{\text{ref}}}{\partial T}\frac{1}{V_{\text{ref}}} + \frac{\mu_T}{T}. \tag{7}$$

By differentiating (7) with respect to the temperature, we obtain

$$\frac{\partial V_{\text{ref}}}{\partial T}\frac{1}{V_{\text{ref}}} = \frac{1}{T}. \tag{8}$$

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

$$\frac{\partial f}{\partial T}\frac{1}{f} = \frac{1}{T}(\mu_T + 1). \tag{9}$$

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.

4. Process variation sensitivity

From Eqs. (3)–(5) we can derive the following expression of the oscillation frequency:

$$f = \frac{\sqrt{K_3K_8}}{2C_T\sqrt{2}(1-M)(1-N)}V_{\text{ref}}. \tag{10}$$

If the matching errors are neglected, V_{ref}, M, and N in (10) 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 α ($V_{\text{ref}} = \alpha V_{dd}$), which is only affected by matching errors. Therefore, the sensitivity of the oscillation frequency to process variations is due to the carrier mobility μ and to the accuracy of the capacitor C_T. To first order, from (10), we have

$$\frac{\mathrm{d}f}{f} = \frac{\mathrm{d}\mu}{\mu} - \frac{\mathrm{d}C_T}{C_T}. \tag{11}$$

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 (11), 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.

5. Simulation results and measurements

The proposed current reference circuit has been implemented, simulated, built and tested in AMS 0.35 μm BiCMOS technology. Total 15 samples of the test chip were measured.

In order to evaluate the sensitivity of the oscillation frequency to process variations, a Monte Carlo simulation has also been performed and the results were compared with the data from the test chips. Fig. 4 shows the simulated and measured cumulative distribution function of oscillation frequencies with a supply voltage of 0.8 V. The mean working frequency is 49.7 kHz and the distributions are in reasonable agreement, even if the frequency dispersion is close to 30%. Fig. 4 also includes a frequency distribution function obtained from a simulation with a V_{dd} of 1 V, which exhibit a dispersion close to 3%. Unfortunately, it was not possible to obtain experimental data at 1 V. In fact, even if the oscillator was designed to work up to 1.5 V, its performance degrades for supply voltages higher than about 0.85 V, with a steeply decreasing output frequency (see Fig. 6 right). Using the available design kit, this behaviour cannot be reproduced by simulation, and we have not found a reasonable justification. This strong sensitivity to the supply voltage and process variations requires this oscillator to be used with a process compensating regulated voltage supply [8].

Fig. 5 shows the variation of supply power, again at 0.8 V supply voltage, vs. temperature. As can be seen from Fig. 5, the oscillator exhibits a typical power consumption of 616 nW. While simulations predict an almost constant power, test chips show a slight increase (0.3%/°C), possibly connected with the increase of saturation current in pn junctions (well-substrate). Fig. 6 (left) shows, at 0.8 V supply voltage, the temperature stability of output frequency. Both simulations and measurements provided values lower than 0.3%/°C.

The area occupation on the chip is 0.24 μmm^2. Table 1 reports a comparison of the performances of the proposed oscillator with those of other designs already reported in the literature. We can note that the proposed oscillator has a very low power-to-frequency ratio (12 pW/Hz), the lowest absolute power, 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 1, which, however, have the drawback of requiring additional external components, contrary to our proposed solution.

6. Conclusion

A low-frequency oscillator implemented in AMS 0.35 μm BiCMOS 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 0.8 V and of a power consumption of about 0.65 μW. Power-to-frequency ratio and temperature sensitivity are significantly smaller than those obtained by comparable designs (i.e. without external passive elements) in literature.

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