INTEGRATION, the VLSI journal 55 (2016) 57–66

Contents lists available at ScienceDirect

INTEGRATION, the VLSI journal

journal homepage: www.elsevier.com/locate/vlsi

A low-power wide tuning-range CMOS current-controlled oscillator

Kourosh Hassanli [a], Sayed Masoud Sayedi [a], Rasoul Dehghani [a], Armin Jalili [b], J. Jacob Wikner [b]

[a] Department of Electrical and Computer Engineering, Isfahan University of Technology, Isfahan 84156-83111, Iran
[b] Department of Electrical Engineering, Linköping University, SE-58183 Linköping, Sweden

ARTICLE INFO

Article history:
Received 16 October 2015
Received in revised form
11 March 2016
Accepted 15 March 2016
Available online 22 March 2016

Keywords:
Current-controlled oscillator
Low power
Current-based data converter
Wide tuning-range oscillator
Sensitivity

ABSTRACT

This paper presents a low-power, small-size, wide tuning-range, and low supply voltage CMOS current-controlled oscillator (CCO) for current converter applications. The proposed oscillator is designed and fabricated in a standard 180-nm, single-poly, six-metal CMOS technology. Experimental results show that the oscillation frequency of the CCO is tunable from 30 Hz to 970 MHz by adjusting the control current in the range of 100 fA to 10 μA, giving an overall dynamic range of over 160 dB. The operation of the circuit is nearly independent of the power supply voltage and the circuit operates at supply voltages as low as 800 mV. Also, at this voltage, with control currents in the range of sub-nano-amperes, the power consumption is about 30 nW. These features are promising in sensory and biomedical applications. The chip area is only $8.8 \times 11.5\ \mu m^2$.

1. Introduction

Oscillators are essential circuit blocks in modern communication systems, instrumentations, signal processors, signal generators, phase-locked loops, timing recovery circuits, frequency modulators, and data converters. Among different oscillator types, LC oscillators are more widely used because of their better phase noise performance. However, they have a narrow tuning-range, and relatively large die area due to the inductor [1–3], so they are not suitable for wide tuning-range data converter applications. On the other hand, many of the existing current-controlled oscillators are based on multi-vibrator or ring oscillator structures [4–12]. Compared to LC oscillators, these structures usually have poor phase-noise characteristics and poor frequency stability at very high oscillation frequencies; but they have wider tuning-range and also relatively smaller die size [13–15]. The multi-vibrator and ring oscillator structures are usually constructed based on multiple delay elements such as logic gates and operational amplifiers. In the case of logic gates, the control current is adjusted to control the rise/fall time of each stage. In the case of operational amplifiers, the control current is adjusted to control the bias currents, so that the gain of the operational amplifiers are modified in order to tune the oscillation frequency [5–7].

In most previously reported multi-vibrator and ring oscillator structures, the required current variation is large, several nano-amperes to micro-amperes, to make significant changes in the oscillation frequency. Furthermore, these structures have relatively high power consumption [4,6,7,14–19]. As a result, these structures are not applicable in cases such as current converters in portable biomedical and sensory applications where currents must usually be in the range of femto- to nano-amperes. This very low current range cannot be directly processed by analog circuits, nor easily converted to digital signals. One solution, as proposed in [19], is to first integrate the control current for a specific period of time, as a voltage/charge, and then convert the obtained voltage/charge to a digital signal based on a pulse modulation scheme. Wang et al. have proposed a CCO based on a multi-vibrator structure that operates with a control current in the range of nano-amperes; but it consumes high power due to short-circuit currents [20]. Zhao et al. in [21] have attempted to reduce the power consumption of the proposed circuit in [20]. The modified circuits in [21] are not able to sense currents in the range of sub-nano-amperes, and also the power consumption increases at low current values due to an increase of short-circuit time.

In sensory and biomedical applications, the currents generated by the sensor are in the range of femto- to nano-amperes and the power consumption is the outmost important parameter. This work presents a CCO based on a modified multi-vibrator structure to design a data converter for portable biomedical and sensory applications. The circuit directly converts currents in the range of femto- to micro-amperes with a reasonable precision. The proposed CCO has low area, wide dynamic range, low power

E-mail addresses: k.hassanli@ec.iut.ac.ir (K. Hassanli), m_sayedi@cc.iut.ac.ir (S.M. Sayedi), dehghani@cc.iut.ac.ir (R. Dehghani), armin.jalili.sebardan@liu.se (A. Jalili), jacob.wikner@liu.se (J.J. Wikner).

http://dx.doi.org/10.1016/j.vlsi.2016.03.001
0167-9260/

consumption and high conversion ratio. It can be used as an interface for measuring or processing of very low currents. Fig. 1 illustrates the CCO as an interface to measure the sensor current. The current is applied to the CCO to be converted to a pulse frequency modulated (PFM) signal. The frequency detector determines the frequency of the output signal to obtain the equivalent sensor current.

The rest of this paper is organized as follows. The structure of a multi-vibrator based CCO is described in Section 2. Section 3 presents the proposed modified multi-vibrator based CCO circuit. A chip implementation and simulation results of the circuit are presented in Section 4. Experimental results are provided in Section 5; and finally, the work is concluded in Section 6.

2. A current-controlled oscillator based on a multi-vibrator structure

A multi-vibrator based current-controlled oscillator as presented in [20] is shown in Fig. 2. It consists of one latch (the INV1 and INV2 pair), four NMOS transistors N_1 to N_4, and two PMOS switches P_1 and P_2. The value of the output signal (V_3 or V_4) is determined by the state of the latch, which is controlled by the pull-down transistors, N_3 and N_4.

Depending on the state of the latch, one of the PMOS transistors (P_1 or P_2) is turned on and the control current I_{in} is steered to charge one of the nodes V_1 or V_2 accordingly. Consequently, when the slow-rising voltage V_1 or V_2 becomes high enough, one of the pull-down transistors N_3 or N_4 is turned on, the state of the latch is changed, and the control current is switched to charge the other node. By this, the control current is switched alternately to charge nodes V_1 and V_2 and generate the corresponding output pulses.

The charging process is done gradually, so transistor N_3 (or N_4) is on for a period of time until V_3 (or V_4) is pulled down and state of the latch is changed. Thus, the power dissipation of the circuit is relatively high due to the short-circuit currents drawn from the

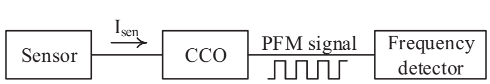

Fig. 1. The proposed current-controlled oscillator used as a current converter.

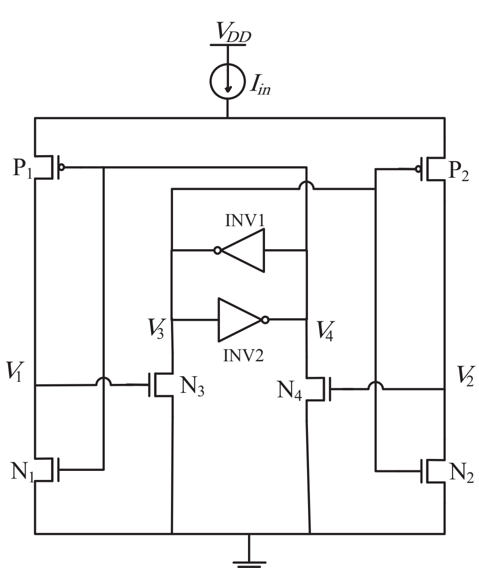

Fig. 2. Schematic diagram of a multi-vibrator based current-controlled oscillator [20].

latch by the pull-down transistors. Zhao et al. in [21] have introduced two modified CCO circuits based on the circuit in [20]. In the modified structures, the power consumption is reduced by eliminating the mentioned short-circuit currents by buffering the slow-rising voltages. This sharpens the applied pulses to the gate of the pull-down transistors. Despite this improvement, the circuits cannot detect very low control currents because of the effect of short-circuit currents at the buffer stages. Moreover, the power consumption is increased for low control currents due to short-circuit paths in the buffer stages. The proposed circuits in [20,21] have a wide tuning-range, and low area, and are very sensitive to the control current but their power consumption is high and they cannot detect very low currents. The purpose of present work is to design a low power wide tuning-range CCO with the ability of detecting currents in the range of femto- to micro-amperes.

3. The proposed current-controlled oscillator

The circuit schematic of the proposed CCO is shown in Fig. 3. The circuit consists of a latch (the INV1 and INV2 pair) to control the switches and generate the output pulses, four inverters INV3, INV4, INV5, and INV6 to decrease power consumption, and 10 MOS switches P_1–P_4 and N_1–N_6 to change the state of the latch. The voltage signals V_{out} and V_{out}' are the complementary outputs of the CCO. The circuit operation is as follows:

When voltage V_7 is high, transistor P_1 is turned off and transistor N_1 is turned on to discharge node V_1 to zero. During this time, V_8 is low, transistor N_2 is turned off and transistor P_2 is turned on to steer control current I_{in} to charge the capacitance (parasitic capacitors plus gate-source capacitor) at node V_2. Transistor N_4 is turned on when the rising voltage V_2 is close enough to the threshold voltage of the NMOS transistor. At this time, node V_4 is discharged. Similarly, pull-down transistor N_5 is turned on when voltage V_4 is close to half the supply voltage. In this case, the state of the latch is changed. The control current is switched to charge node V_1, and node V_2 is discharged. This process is performed alternatively to generate output pulses.

Inverters INV3 and INV4 are employed to convert slow-subsiding voltages V_3 and V_4 into sharp pulses to reduce the short-circuit currents that flow in the path of the PMOS transistors of the latch and the NMOS pull-down transistors. Inverters INV5 and INV6 are used to turn off pull-up transistor P_3 or P_4 when

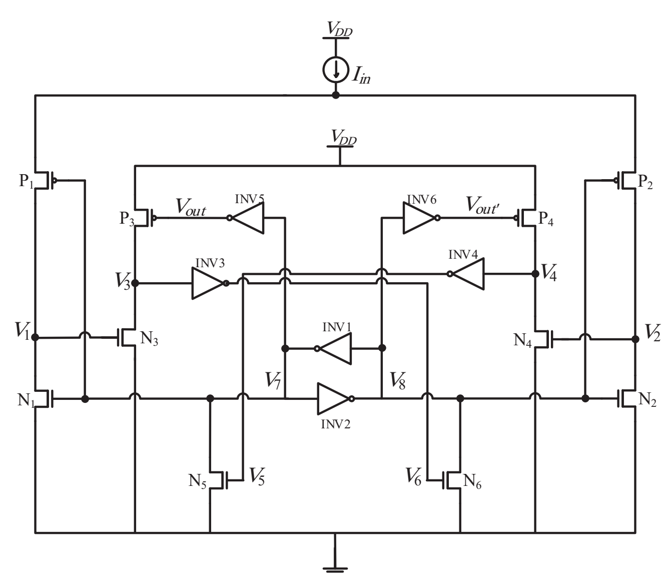

Fig. 3. The circuit schematic diagram of the proposed current-controlled oscillator.