

# Supply Voltage and Temperature Insensitive Current Reference for the 4 MHz Oscillator

Chi-Hsiung Wang  
Dept. of E. E.  
Tamkang University  
New Taipei City, Taiwan  
chwang0327@gmail.com

Cheng-Feng Lin  
Dept. of E. E.  
Tamkang University  
New Taipei City, Taiwan  
792350257@s92.tku.edu.tw

Wei-Bin Yang  
Dept. of E. E.  
Tamkang University  
New Taipei City, Taiwan  
robin@ee.tku.edu.tw

Yu-Lung Lo  
Dept. of E. E.  
National Kaohsiung Normal  
University  
Kaohsiung, Taiwan  
yllo@nkn.edu.tw

**Abstract**—This paper presents a 4 MHz current control ring oscillator with a new temperature and supply voltage immune current reference implemented by 0.35 $\mu$ m CMOS technology. Compared to the conventional oscillator with current reference techniques, the proposed approach shows a significant improvement for the sensitivities of temperature and supply voltage. The current reference is designed by combining positive and negative temperature effect circuits, such that it can exempt from the temperature and supply voltage variations. By HSPICE simulation, this new current reference is insensitive to the supply voltage with variations of  $-0.47\%$ ~ $-0.67\%$  over the supply voltage range of 2.97V to 3.63V, and it is also insensitive to the temperature with variation of 366 ppm/ $^{\circ}$ C over the temperature range of  $-40^{\circ}$ C to  $100^{\circ}$ C. The proposed oscillator frequency is insensitive to the supply voltage with variations of  $-15\%$ ~ $-20\%$  over the supply voltage range of 2.97V to 3.63V, and it is insensitive to temperature with variation of 404 ppm/ $^{\circ}$ C over the temperature range of  $-40^{\circ}$ C to  $100^{\circ}$ C.

**Keywords**- current reference, supply voltage, ring oscillator

## I. INTRODUCTION

Current reference is an essential block in many analog circuits, such as the bias sources for oscillators, amplifiers, and phase lock loops. For those applications, the current references must be insensitive to supply voltage and temperature variations. Since it is easy to implement a voltage reference by bandgap circuit, the current references can be derived from voltage references by applying Ohm's law for voltage to current conversion [1]. However, this kind of current reference may take more silicon area since it contains some bipolar transistors, operational amplifier, and resistors. The current reference proposed by Sansen et al. [2] is a circuit without resistor. With an absolute temperature  $T$ , the current is proportional to  $T^{0.5}$  with 3.5V minimum supply voltage. The current reference proposed by Oquey et al. [3] is a low voltage approach using the PTAT-like technique. Here the resistor  $R$  is replaced by an n-channel MOSFET working in the triode region. Like [2], the output current is proportional to  $T^{0.5}$ . It can work with a power supply as low as 1.2V and produce 1-100 nA output current. However, this current reference is strongly dependent on the supply voltage.

In this research work, we present a new current reference. The proposed current reference consists of two components.

The first one is adopted from the well-known circuit given by Razavi's text book [4], which uses two PMOS transistors as current mirror and a resistor to define the output current. This circuit exhibits a positive supply voltage coefficient and the current is also proportional to the absolute temperature (PTAT). The second component has the characteristics of negative supply voltage coefficient and negative temperature coefficient. The two circuits can compensate each other such that it provides a current insensitive to supply voltage and temperature. We apply the proposed current reference further to the current control ring oscillator and make the ring oscillator have low sensitivity to temperature and supply voltage variations.

The rest of this paper is organized as follows. Section 2 describes the circuit descriptions and analyses. The simulation results are addressed in Section 3 and a brief conclusion is given in Section 4.

## II. CIRCUIT DESCRIPTION AND ANALYSIS

In this section, the circuit architecture and associated operating principles of temperature and supply voltage compensated ring oscillator are analyzed and discussed. The system block diagram of the current control ring oscillator with temperature and supply voltage compensated scheme is shown in Fig. 1(a); the system block diagram of the temperature and supply voltage compensated current reference is shown in Fig. 1(b). The current reference is comprised by two parts, positive temperature current reference circuit and negative temperature current reference circuit, and the details of the current references are described in the following subsection.

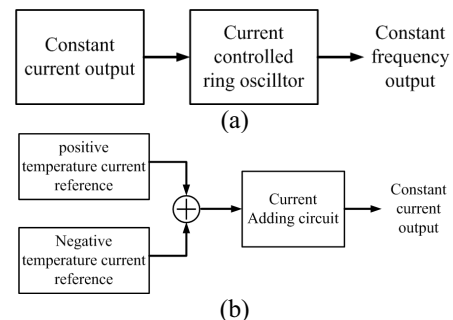


Figure 1. (a) Temperature and supply voltage compensated ring oscillator (b) Temperature and supply voltage compensated current reference

### A. Positive temperature current reference circuit

A well-known conventional current reference given by Razavi [4] is shown in Fig. 2. According to Fig. 2, the output current is given as follows:

$$I_{10} = \frac{2}{\mu_n C_{ox} \left(\frac{W}{L}\right)} \frac{1}{R^2} \left(1 - \frac{1}{\sqrt{K}}\right)^2, \quad (1)$$

where  $K$  is the ratio of the size of  $M_{N17}$  to  $M_{N18}$ . From (1), the current reference is insensitive to the supply voltage. In fact, based on the simulation results depicted in Fig. 3 with a supply voltage range of 2.97V to 3.63V, the current reference still depends on the supply voltage slightly for the channel length modulation of transistors  $M_{P12}$  and  $M_{P13}$ .

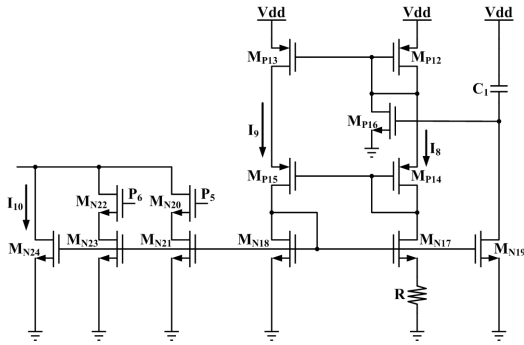


Figure 2. Positive temperature current reference circuit

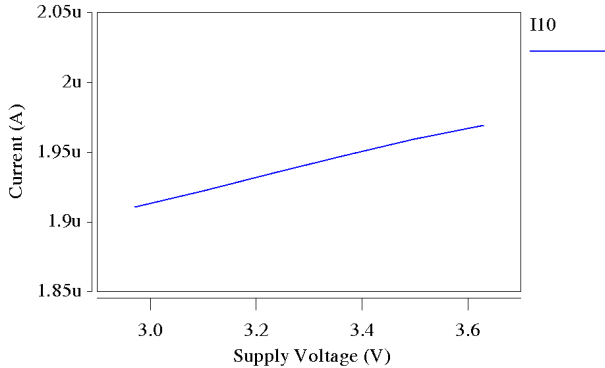


Figure 3. The simulation of currents versus supply voltage for the positive temperature current reference

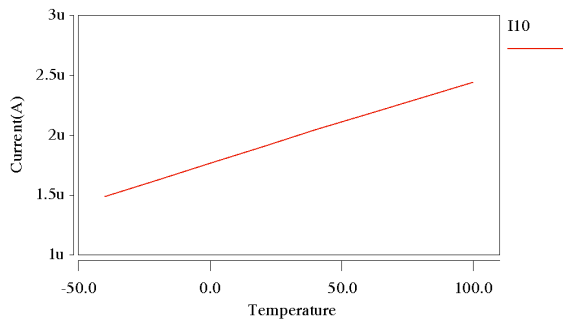


Figure 4. The simulation of currents versus temperature for the positive temperature current reference

Moreover, due to the mobility in the denominator of (1), this current reference has the effect of positive temperature coefficient as shown in Fig. 4.

### B. Negative temperature current reference circuit

The negative temperature current reference circuit proposed here is to compensate the positive temperature current reference. At first, we propose two different types of current references as the basic current operational component.

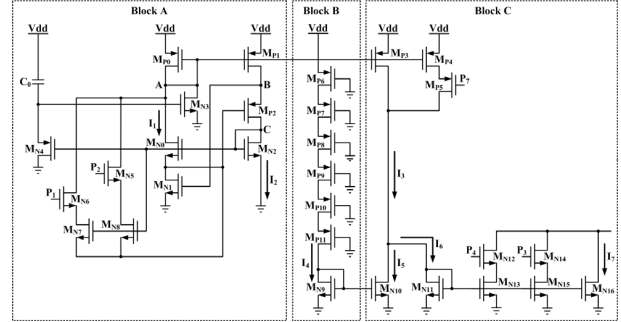


Figure 5. Negative temperature current reference circuit

The first component shown in block A of Fig. 5 is almost the same as the known current reference depicted in Fig. 2 except that the resistor is replaced by transistor  $M_{N1}$  which works in the triode region. Besides, transistor  $M_{P2}$  is placed in between  $M_{P1}$  and  $M_{N2}$  to provide a bias voltage for  $M_{N1}$ . As a result,  $M_{N1}$  works in the triode region, and  $I_1$  can be expressed as:

$$\begin{aligned} I_1 &= \mu_n C_{ox} \left(\frac{W}{L}\right)_{N1} (V_{GS} - V_{TH}) V_{DS} \\ &= \mu_n C_{ox} \gamma V_{DS} \left(\frac{W}{L}\right)_{N1} \left(V_{DD} - \frac{V_{TH}}{\gamma}\right) \\ &= \alpha_1 \left(\frac{W}{L}\right)_{N1} (V_{DD} - \beta_1) \end{aligned} \quad (2)$$

where  $V_{GS} = \gamma \times V_{DD}$ ,  $\alpha_1 = \mu_n C_{ox} \gamma V_{DS}$ , and  $\beta_1 = V_{TH} / \gamma$ . The second component of the proposed current reference shown in block B of Fig. 5 composes of  $M_{P6} - M_{P11}$  and  $M_{N9}$ . Transistors  $M_{P6} - M_{P11}$  all work in the triode region. Based on HSPICE simulation, the current reference of these two components will be almost linearly dependent on the supply voltage. Therefore,  $I_4$  can be expressed as:

$$\begin{aligned} I_4 &= \mu_n C_{ox} \left(\frac{W}{L}\right)_{N9} \left[ (V_{GS} - V_{TH}) V_{DS} - \frac{1}{2} V_{DS}^2 \right] \\ &= \alpha_2 \left(\frac{W}{L}\right)_{N9} (V_{DD} - \beta_2) \end{aligned} \quad (3)$$

where  $V_{GS} = V_{DD}$ ,  $\alpha_2 = \mu_n C_{ox} V_{DS}$ , and  $\beta_2 = V_{TH} + 1/2(V_{DS})$ . According to blocks A and B of Fig. 4,  $M_{P0}$  and  $M_{P3}$  are a set of current mirror;  $M_{N9}$  and  $M_{N10}$  are another set of current mirror. By adjusting the ratio of  $(W/L)_{P3}$  and  $(W/L)_{N10}$ , we can make  $\alpha_1(W/L)_{P3}$  to be smaller than  $\alpha_2(W/L)_{N10}$ . According to

the operation of current subtraction ( $I_6 = I_3 - I_5$ ), current  $I_6$  presents the negative supply voltage coefficient due to currents  $I_5$  behaving a larger supply voltage coefficient than  $I_3$ . Moreover, current  $I_6$  also presents the negative temperature coefficient due to the mobility.

### C. Current Adding circuit

According to block C of Fig. 5 and Fig. 2,  $I_7$  and  $I_{10}$  are the duplicated currents of the negative temperature current reference and the positive temperature current reference, respectively. By adding currents of  $I_7$  and  $I_{10}$ , we can derive a new current reference  $I_{11}$  which has low sensitivity to temperature and supply voltage variations. Fig. 6 shows the combination circuit to generate the temperature and supply voltage immune current  $I_{11}$  and the currents ( $I_{12}$  and  $I_{13}$ ) required for the current control ring oscillator.

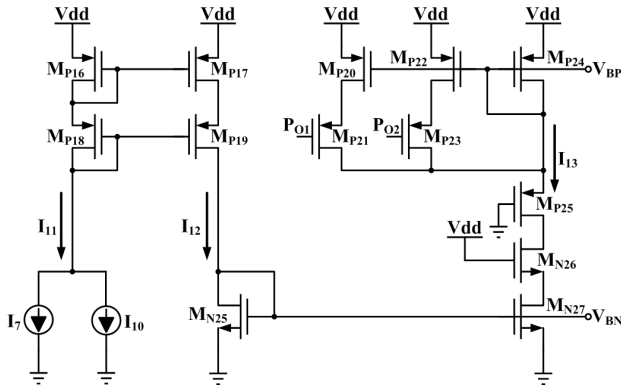


Figure 6. Current Adding circuit

### D. Current Controlled Oscillator

Fig 7 shows the current control oscillator (CCO). In Fig. 7, INV is a dummy circuit. The required references are provided from the circuit described in the previous subsection. The buffer can drive the capacitance loading as high as 30pF, and the designed output frequency is 4MHz.

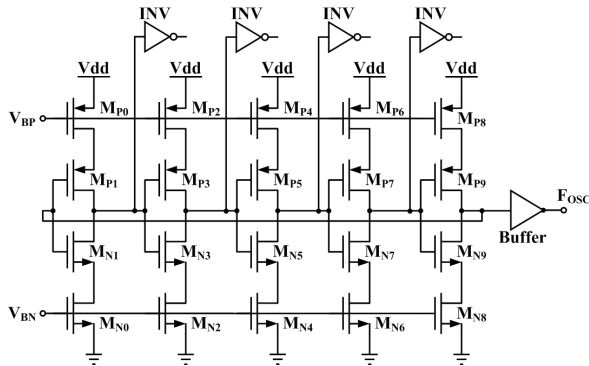


Figure 7. Current Controlled Oscillator (CCO)

## III. SIMULATION RESULTS

The HSPICE simulator has been performed on the temperature and supply voltage compensated ring oscillator using TSMC 0.35um models for the MOS device. Fig. 8 shows the current reference versus voltage variation simulation results.  $I_7$  and  $I_{10}$  exhibit linear relationship with the supply voltage from 2.97V to 3.63V. It is clear that current  $I_{11}$ ,  $I_{11}=I_7+I_{10}$ , is weakly dependent on the supply voltage from 2.97V to 3.63V. Fig. 9 shows the current reference versus temperature variation simulation results. According to the simulation,  $I_7$  has the effect of negative temperature coefficient, and  $I_{10}$  has the effect of positive temperature coefficient from  $-40^\circ\text{C}$  to  $100^\circ\text{C}$ . Moreover, it is clear that current  $I_{11}$ ,  $I_{11}=I_7+I_{10}$ , shows the insensitivity to the temperature variations.

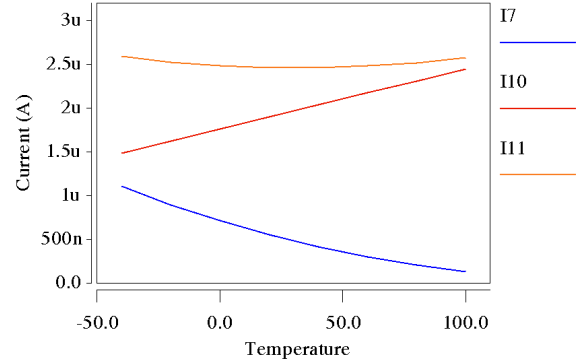


Figure 8. The simulation results of the currents versus supply voltages

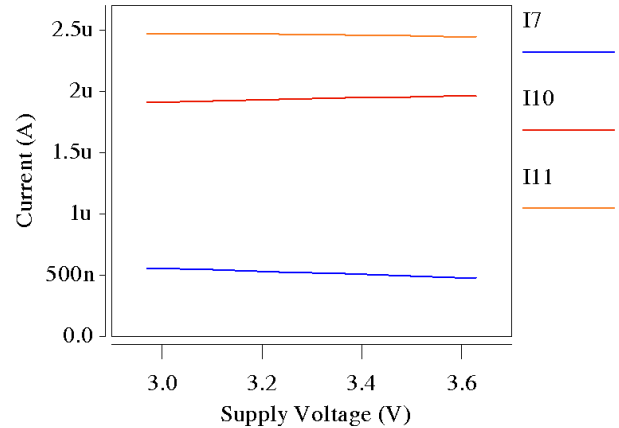


Figure 9. The simulation results of the currents versus different temperature

The simulation results of the output frequency of the temperature and supply voltage compensated ring oscillator is shown in Figs. 10 and 11. Because the current reference  $I_{13}$  possesses low sensitivity to temperature and supply voltage variations according to Fig. 6, the oscillator frequency is proved to be insensitive to supply voltage with variations of  $-15\% \sim 20\%$  over the supply voltage range of 2.97V to 3.63V and insensitive to temperature with a variation of 404 ppm/ $^\circ\text{C}$  over a temperature range of  $-40^\circ\text{C}$  to  $100^\circ\text{C}$ . The performance specification and comparisons with other research works of the ring oscillator are shown in Table. 1.

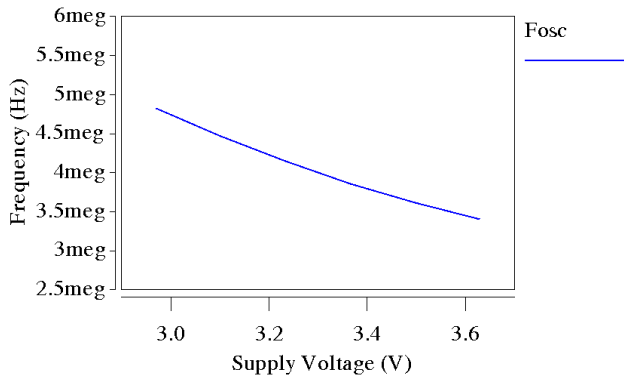


Figure 10. The simulation results of the CCO frequency versus supply voltages

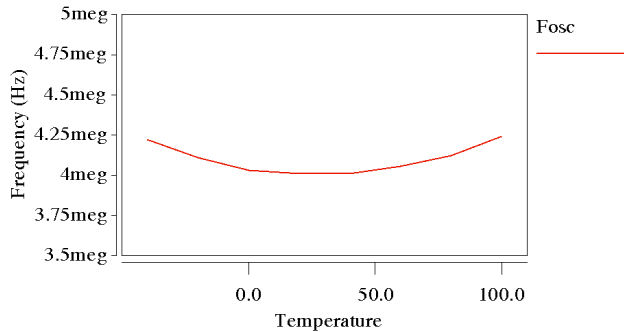


Figure 11. The simulation results of the CCO frequency versus different temperature

TABLE I. PERFORMANCE SUMMARY AND COMPARISONS

Parameters	[5]	[6]	[7]	[8]	[9]	This work
Process ( $\mu\text{m}$ )	0.5	0.25	0.28	0.25	0.5	0.35
Frequency (Hz)	80k	7M	2.4G	800M	12.8M	4M
Supply Voltage (V)	1	2.5	2.5	2.5	3	3.3
Consume current ( $\mu\text{A}$ )	1.14	600	7680	7580	133	67
Temperature ( $^{\circ}\text{C}$ )	0 ~80	-40 ~125	-40 ~120	N/A	-40 ~125	-40 ~100
Area ( $\text{mm}^2$ )	0.24	1.6	0.0121	N/A	0.1848	0.02

#### IV. CONCLUSIONS

In this paper we propose a new negative temperature current reference circuit to compensate the positive temperature current reference and combine these two current references to

form a new current reference which can exempt from the effects of temperature and supply voltage variations. This temperature and supply voltage immune reference is further applied to design a 4MHz current control oscillator. The simulation results prove that the proposed current reference is insensitive to the supply voltage with a variation of  $-0.47\%$ ~ $-0.67\%$  over a supply voltage range of 2.97V to 3.63V, and it is also insensitive to temperature with variation of 366 ppm/ $^{\circ}\text{C}$  over the temperature range of  $-40^{\circ}\text{C}$  to  $100^{\circ}\text{C}$ . The simulations also show that the 4MHz current control oscillator whose output frequency is insensitive to the supply voltage with variation of  $-15\%$ ~ $-20\%$  over the supply voltage range of 2.97V to 3.63V, and it is insensitive to temperature with variation of 404 ppm/ $^{\circ}\text{C}$  over the temperature range of  $-40^{\circ}\text{C}$  to  $100^{\circ}\text{C}$ .

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