ELectronics EXpress

A temperature-compensated CMOS ring oscillator for DC-DC converters

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Abstract: A novel current controlled CMOS ring oscillator is presented in this paper. Specially circuit structure and transistor parameters design is used to obtain good temperature coefficient. The designed ring oscillator circuit has been used in a CMOS step-up switching regulator controller which has been implemented using a $0.5\,\mu$m double poly double metal CMOS technology. The test result shows that the frequency is about 1.2 MHz and the error ($\Delta f/f$) is about 3.5% in the temperature range −20–100℃. The circuit is quite suitable for DC-DC converters.

Keywords: temperature compensated, ring oscillator, current reference

Classification: Integrated circuits

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1 Introduction

The ring oscillator is a crucial component that has been widely used in analog and digital applications [1, 2, 3, 4]. It is an important circuit block in DC-DC converters due to its compact design, wide tuning range, and low power consumption [1]. In some design of DC-DC converters, temperature-independent switching frequency (f_{osc}) is quite important. As you know, loop compensation is usually applied to voltage mode or current mode switching regulator and it is related to the oscillation frequency of the switching regulator. If the temperature coefficient of oscillation frequency is

DOI: 10.1587/elex.10.20130833
Received October 23, 2013
Accepted November 01, 2013
Publicized November 14, 2013
Copyedited November 25, 2013

not good, the loop system will be unstable. The oscillator structure is better to be simple in order to obtain lower cost.

The traditional ring oscillator is usually designed with no temperature compensated component. In many commercial products, external low-temperature coefficient capacitors and resistors are used for generating the adjustable and low temperature coefficient f_{osc} [1]. However this approach increases the cost and impacts the board size. In some other design, low temperature coefficient current, two voltage references and comparators are needed to generate temperature-independent frequency. The circuit is more complicated and the cost is higher. In this paper, we present a current controlled temperature-compensated CMOS ring oscillator which is simple and quite suitable for DC-DC converters.

2 The proposed ring oscillator circuit

The proposed ring oscillator circuit is shown in Fig. 1, which is a seven-stage structure. This circuit structure alternatively charges two capacitors (C1 and C2) with the constant current and quickly discharges them with NMOS transistors. As shown in Fig. 1, the gate voltage of N0 is a voltage reference V_{ref}. Voltage reference circuit is one of the most basic circuit modules in DC-DC converters main structure, which is stable over process, power supply voltage and temperature variations. Bandgap voltage reference and some other structure are usually used. The proposed oscillator shares the same voltage reference with the main structure. And V_{ref} in Fig. 1 is designed to be more than the NMOS threshold voltage. The PMOS P1, P2, P5 and P8 are designed to have the same gate voltage VB1 and the same W/L ratio k_2. So they have the same source-drain current I_0. The W/L ratio of N0, N4 and N7 are also designed the same. Thus the reverse voltage of N4 and N7 is V_{ref}, which has low-temperature coefficient.

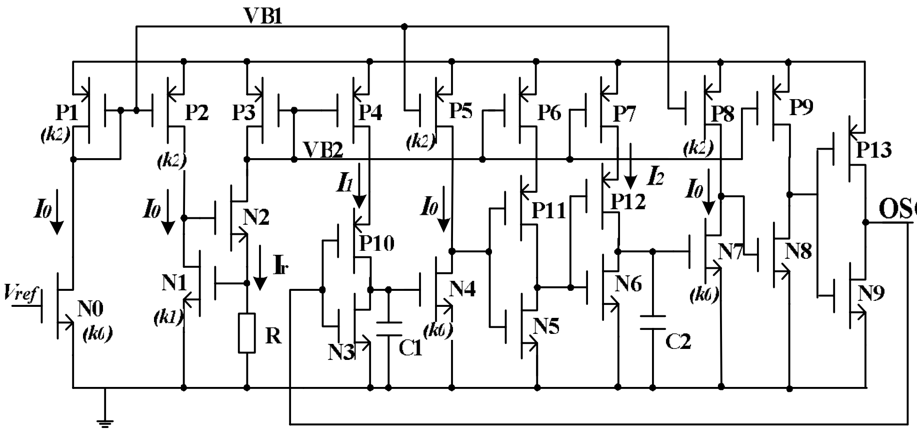

Fig. 1. The proposed ring oscillator circuit

The period of the oscillator is

$$T = T_{on} + T_{off},$$

where T_{on} and T_{off} are respectively approximately equal to $V_{ref}{}^{*}C2/I_2$ and $V_{ref}{}^{*}C1/I_1$. So the frequency of the circuit is mainly determined by the charge current I_1 and I_2, the capacitor value of C1 and C2, the reverse voltage of N4 and N7 V_{ref}. PIP(Poly-Insolator-Poly) and MIM(Metal-

DOI: 10.1587/elex.10.20130833
Received October 23, 2013
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IEICE Electronics Express, Vol.10, No.22, 1–5

Insolator-Metal) capacitors are usually be used to achieve low temperature coefficient and high precision. We can obtain low temperature coefficient frequency if the charge current I_1 and I_2 are designed to be temperature-independent. The detail design method is shown in the following.

As shown in Fig. 1, the gate to source voltage of N1 is

$$\begin{aligned} V_{gs1} &= V_{thn} + \sqrt{\frac{2I_0}{\mu_n C_{ox} k_1}} = V_{thn} + \sqrt{\frac{\mu_n C_{ox} k_0 \left(V_{ref} - V_{thn}\right)^2}{\mu_n C_{ox} k_1}} \\ &= V_{thn} + \sqrt{\frac{k_0}{k_1}}\left(V_{ref} - V_{thn}\right) = \sqrt{\frac{k_0}{k_1}} V_{ref} + \left(1 - \sqrt{\frac{k_0}{k_1}}\right) V_{thn} \end{aligned} \tag{1}$$

where V_{thn} is NMOS threshold voltage, μ_n is the electron mobility, C_{ox} is the oxide capacitance per unit area.

The threshold voltage of NMOS linearly decreases with temperature, which is modelled

$$V_{thn} = V_{thn}(T_0)[1 + K_M(T - T_0)] \tag{2}$$

where K_M is the temperature coefficient of the NMOS threshold voltage, T is the absolute temperature and T_0 is the absolute temperature at which K_M is evaluated.

Solving Eq. (1) and Eq. (2) for V_{gs1} gives

$$\begin{aligned} V_{gs1} = &\sqrt{\frac{k_0}{k_1}} V_{ref} + \left(1 - \sqrt{\frac{k_0}{k_1}}\right) V_{thn}(T_0) \\ &+ \left(1 - \sqrt{\frac{k_0}{k_1}}\right) V_{thn}(T_0) K_M (T - T_0) \end{aligned} \tag{3}$$

If $k_0 = k_1$, then $V_{gs1} = V_{ref}$ and the current of PMOS P3 is

$$I_r = \frac{V_{gs1}}{R} = \frac{V_{ref}}{R} \tag{4}$$

The low temperature coefficient current I_r can be obtained through selecting low temperature coefficient resistor R or two series resistors with opposite temperature coefficient.

If $k_0 \neq k_1$, let $S_1 = \sqrt{\frac{k_0}{k_1}} V_{ref} + \left(1 - \sqrt{\frac{k_0}{k_1}}\right) V_{thn}(T_0)$, $S_2 = \left(1 - \sqrt{\frac{k_0}{k_1}}\right) V_{thn}(T_0)$, then

$$V_{gs1} = S_1 + S_2 K_M (T - T_0) \tag{5}$$

Assumed that the resistor R also has a temperature coefficient, modelled as

$$R = R(T_0)[1 + K_R(T - T_0)] \tag{6}$$

$$I_r = \frac{V_{gs1}}{R} = \frac{S_1 + S_2 K_M (T - T_0)}{R(T_0)[1 + K_R(T - T_0)]} \tag{7}$$

To obtain that the current I_r is insensitive to temperature, we make $\frac{\partial I_r}{\partial T} = 0$, then the following equation can be obtained.

$$S_2 K_M R(T_0)[1 + K_R(T - T_0)] - [S_1 + S_2 K_M (T - T_0)] R(T_0) K_R = 0 \tag{8}$$

DOI: 10.1587/elex.10.20130833
Received October 23, 2013
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Copyedited November 25, 2013

Thus we can get

$$S_2 K_M = S_1 K_R \tag{9}$$

That is

$$\frac{K_M}{K_R} = \frac{\sqrt{\frac{k_0}{k_1}} V_{ref}}{\left(1 - \sqrt{\frac{k_0}{k_1}}\right) V_{thn}(T_0)} + 1 \tag{10}$$

In Eq. (10), K_M, K_R and $V_{thn}(T_0)$ are technology dependent. V_{ref} is a known value. Therefore we can get a low temperature coefficient current I_r through proper k_0 and k_1 design. The charge current I_1 and I_2 are temperature-independent. As mentioned above, the reverse voltage of N4 and N7 are also temperature-independent. Thus Low temperature coefficient frequency of the ring oscillator is obtained.

3 Results

The proposed ring oscillator circuit has been used in a CMOS step-up DC-DC converter. The circuit has been implemented in 0.5 μm double poly double metal CMOS technology. In the process, the capacitor C1 and C2 are implemented with PIP(Poly-Insolator-Poly) capacitor. V_{ref} is designed to be 0.8 V and its temperature coefficient is 54 ppm/℃. Fig. 2 shows the photograph of the controller, in which the oscillator block is indicated. The area of oscillator is about 180 μm × 90 μm.

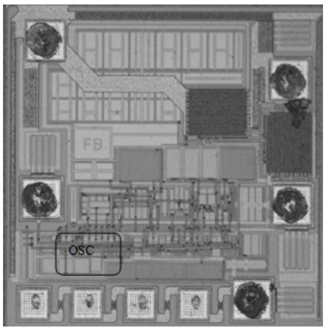

Fig. 2. The photograph of the designed chip

The oscillator circuit is designed to present a mainly 1.2 MHz frequency. The operating current of the circuit is about 45 μA. The whole circuit has been tested with the temperature range of −20℃ to 100℃ under 4 V supply voltage. The test result is shown in Fig. 3. When the temperature changes from −20℃ to 100℃, the frequency changes about 0.042 MHz. The error ($\Delta f/f$) is about 3.5% in the temperature range −20–100℃.

In [1], a ring oscillator for DC-DC converters has also been proposed. It is implemented in 0.35 μm CMOS technology and the error is 3.33% in the temperature range 0℃ to 100℃. But the circuit contains bandgap voltage reference, linear regulator, ring oscillator, level shifting and temperature independent current. The circuit is more complex. And its chip area is 450 μm × 360 μm, which is quite larger than the area of the proposed oscillator. However, the proposed oscillator uses the existing voltage

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Accepted November 01, 2013
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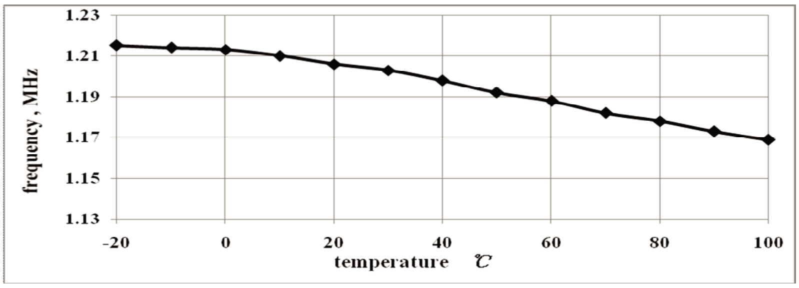

Fig. 3. Measured frequency at different temperature

reference in DC-DC converters and improves the charge and discharge structure of traditional oscillator in order to obtain a temperature compensated frequency. The proposed circuit is quite simple and easy to implement. The frequency is also easy to adjust for different DC-DC converters. The accuracy is sufficient for the switched-mode regulator design. In [5], temperature and process compensation are both studied to obtain good performance. But the power consumption of the circuit was about 1.5 mW, which is quite larger than the proposed circuit. In this paper process compensation circuit is not considered. So further research based on the proposed circuit theory is ongoing. Ring oscillator with simple structure, lower temperature coefficient and lower process dependence is being studied now.

4 Conclusion

In this paper, a current controlled CMOS ring oscillator with good temperature coefficient has been proposed. A novel temperature-compensated method has been presented through circuit structure and transistor parameters design. The structure has been successfully used in CMOS step-up switching regulator controller and achieved good performance. The ring oscillator circuit is quite suitable for DC-DC converters.

Acknowledgments

The paper is supported by national natural science foundation of China (No.61274080) and Natural science fund in Jiangsu Province (No. BK2011753).

DOI: 10.1587/elex.10.20130833
Received October 23, 2013
Accepted November 01, 2013
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Copyedited November 25, 2013