Temperature-compensated CMOS ring oscillator for power-management circuits

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The design of a temperature-compensated CMOS ring oscillator is introduced. The concept is to make use of a linear, positively or negatively temperature-sloped supply voltage to power-up the ring oscillator. Experimental results show that the oscillation frequency remains fairly constant using the proposed scheme.

Introduction: Supply- and temperature-independent switching frequency (f_{osc}) is important in the design of switched-mode regulators for power management since this avoids many problems, such as frequency shifting of sub-harmonics in the frequency spectrum. In many commercial products, external low-tempco capacitors and resistors are used for generating the adjustable and low-tempco f_{osc} . However, this approach increases the cost of packaging owing to the extra pins, and it impacts the board size in compact applications. It has been shown by many publications that the temperature effects of mobility of carriers and the threshold voltage of MOSFET can be mutually cancelled, to generate a temperature-independent voltage [1, 2]. Based on this concept, a temperature-independent current (I_{osc}) can be created similarly, such that the charging and discharging currents are constant. Since $f_{osc} \propto 1/I_{osc}$, f_{osc} is a constant as well. The supply voltage is certainly a key parameter to achieve constant I_{osc} , in addition to the size of the transistors.

Fig. 1 Five-stage ring oscillator

Fig. 2 Measured oscillation frequency at different temperatures with constant supply voltage and with temperature-gradient supply voltage
a Constant supply voltage
b Temperature-gradient supply voltage

Analysis of ring oscillator: A five-stage ring oscillator, shown in Fig. 1, has been implemented in 0.35 μm CMOS technology. Fig. 2a shows f_{osc} against temperature and shows large variation of f_{osc} . When V_{DDO} is high ($V_{DDO} = 2.818\text{ V}$ and 2.038 V), f_{osc} decreases with temperature. When V_{DDO} is low ($V_{DDO} = 1.041\text{ V}$), f_{osc} increases with temperature. However, at a particular V_{DDO} ($V_{DDO} = 1.310\text{ V}$), f_{osc} can be kept constant. This reveals a fact that a constant f_{osc} can be achieved by adjusting V_{DDO} . Based on the study, V_{DDO} is designed to be linearly dependent of temperature. The temperature slope of V_{DDO} can be positive or negative, which depends on the required magnitude of V_{DDO} for the required f_{osc} in the applications. A range of about 0.3–5 MHz, which is the typical range of the switching frequency of the regulators, is chosen in this study. From Fig. 2b, it is found that f_{osc} can be kept fairly constant by this approach. The required

temperature slope is not large, so that V_{DDO} is still within the bound of the maximum supply of typical IC technologies.

Fig. 3 Proposed approach

Fig. 4 Micrograph

Fig. 5 Measured oscillation frequency with proposed method and measured pulse trains

Method: The proposed method implemented by a first-order bandgap voltage reference [3] and a linear regulator is shown in Fig. 3. The temperature slope of the reference voltage (V_{REF}) can be adjusted by resistance ratio [3]. Either a positive or a negative linear (approximated) temperature slope can be generated. V_{REF} can be scaled by the linear regulator to generate V_{DDO} . As a result, the ring oscillator is powered by V_{DDO} , which is temperature-sloped and magnitude adjustable. Therefore, V_{DDO} is given by

$$V_{DDO} = kV_{REF} \quad (1)$$

where k is a temperature-independent constant, which is defined by the feedback resistors of the linear regulator [3]. From (1), the temperature dependence can be obtained as

$$\frac{\partial V_{DDO}}{\partial T} = k \frac{\partial V_{REF}}{\partial T} \quad (2)$$

Equation (2) shows that the temperature slope of V_{DDO} can be adjusted by both k and the temperature slope of V_{REF} . The output voltage level of the ring oscillator can simply be restored by a level-shifting circuit. Therefore, the amplitude of the pulse train of the ring oscillator is V_{DD} , but f_{osc} is V_{DD} -independent.

Experimental results: The proposed approach has been implemented in silicon. Fig. 4 shows a micrograph, in which each building block is indicated. The active chip area is about $450 \times 360 \mu\text{m}$, excluding the test pads. Fig. 5 shows a test case that targets $f_{osc} = 1 \text{ MHz}$ at $V_{DD} = 3 \text{ V}$. The error is 3.33% in the temperature range $0\text{--}100^\circ\text{C}$. The accuracy is sufficient for the typical switched-mode regulator design. Fig. 5 also shows a capture of the output waveforms. The ring oscillator is supplied by temperature-dependent V_{DDO} , while V_{DD} is tested at room temperature at about 2.6 and 3.3 V. The amplitudes of the pulse train in the two cases are therefore 2.6 and 3.3 V, while the change of f_{osc} is negligible. This proves that the supply is independent of the proposed implementation.

Conclusions: An approach to power-up a ring oscillator has been introduced, discussed and proved experimentally, by introducing a temperature-sloped and magnitude-adjustable supply voltage. The approach is simple and is helpful in regulator design to eliminate external components.

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