

## Nano-ampere Supply Voltage Insensitive Current References: Design, Analysis and Measurement

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Energy harvesting is a process by which the ambient energy present in the environment is captured and converted to electrical energy to power electronic devices [1]. Current references often play an important role in the analog blocks of those energy harvesting systems. Due to the low power density level of the harvested energy, circuits usually work in sub-threshold and a nano-ampere current reference is often desired.

The self-biasing current reference circuit discussed in [2] can be easily adapted to generate nano-ampere current. The circuit is shown in Fig. 1. M1-M4 and resistor R generate a reference current  $I_{ref}$ . This current is then mirrored by M5 to generate the output current  $I_{out}$ . This reference current has low supply voltage dependence, and the supply sensitivity  $S_{V_{dd}}^{I_{ref}} = \frac{V_{dd}}{I_{ref}} \frac{\partial I_{ref}}{\partial V_{dd}}$  can be below 1%. However, the circuit might experience stability problems. One can break the feedback loop and inject a small signal  $v_{testin}$  at the gate of M1, then the small signal  $v_{testout}$  at the source of M2 is

$$v_{testout} = g_{m1} R v_{testin} \quad (1)$$

For nano-ampere current operation,  $g_{m1} R$  could be larger than unity, so the circuit might oscillate. This has been observed in both circuit simulations and on chip measurements. The current  $I_{out}$  flows through the load and then the voltage drop across the load is measured. In Fig. 2, the measurement shows that the circuit is oscillating with a frequency of 928 Hz.

A nano-ampere current reference circuit using only transistors is presented in [3] and the circuit is shown in Fig. 3, where M1 and M2 both work in the sub-threshold bias regime. M3 and M4 both work in strong inversion but at different regions: M4 is in saturation and it generates the gate voltage of M3; M3 is in the triode region and it operates as a resistor. M5, M6 and M7 are current mirrors with equal sizes. The reference current can be derived as

$$I_{ref} = \frac{2\beta_3^2}{\beta_4} \left( V_T \ln \frac{\beta_1}{\beta_2} \right)^2 \quad (2)$$

Where  $V_T$  is the thermal voltage, and  $\beta_i = \mu C_{ox} \left( \frac{W}{L} \right)_i$ . The stability of this circuit can be studied in a similar way. One breaks the loop at node A and injects a small signal at the gate of M1, and then one can measure the signal at the gate of M2. The gain is less than unity and the system is stable.

Due to channel length modulation effect, the supply dependence of this current reference is usually non-zero and the supply sensitivity can be large. In [4], researchers present a scheme to reduce the supply sensitivity for a circuit working in strong inversion. We designed a nano-ampere sub-threshold circuit with similar scheme. The idea is to generate two reference currents and make them satisfying the two conditions: (1) the two currents are not equal (2) they have equal supply dependences. By doing subtraction, the supply dependence would cancel out in the final non-zero reference current. The whole circuit is shown in Fig. 4. Where M11-M17 generate current  $I_1$ , and this current is mirrored by M18 to  $m \cdot I_1$ ; M21-M27 generate current  $I_2$ , which is mirrored by M28 to  $n \cdot I_2$ . The final reference current is  $I_{ref} = m \cdot I_1 - n \cdot I_2$ . By changing values of  $m$  and  $n$ , one can make the two conditions satisfied and have a low supply sensitivity reference current. The reference current was designed to be 3nA.

The reference current is determined by measuring the voltage drop across the output load  $R_L$ , which can be hundreds of mega-ohms. To reduce the load resistance needed in the measurement, the

output current  $I_{out}$  is increased to 0.1uA by increasing the size of the output transistor  $M_{out}$ . In the measurement, input resistance  $R_M$  of a digital multimeter or oscilloscope cannot be neglected and needs to be taken into consideration as it is comparable to the load resistance  $R_L$ . The equivalent input resistance of the measurement instrument can be determined in the way shown in Fig. 4.  $R_1$  and  $R_2$  are two resistors with values already known.  $R_M$  is the equivalent resistance of the multimeter. By sweeping the input voltage  $V_{in}$  and measuring the output voltage  $V_{out}$ , one can determine  $R_M$  by

$$R_M = \frac{R_1 R_2}{\frac{\Delta V_{in}}{\Delta V_{out}} R_2 - R_1 - R_2} \quad (4)$$

where  $\Delta V_{in}$  and  $\Delta V_{out}$  are changes of input and output voltages. Knowing the equivalent resistance of the multimeter, one can sweep the supply voltage and measure the voltage drop  $V_{measure}$  across the load  $R_L$ , then one can decide the output current, which is equal to  $\frac{V_{measure}}{R_L // R_M}$ .

The chip has been fabricated using AMI 0.5um process. The reference current was designed to be 3nA, which was then mirrored to generate the 0.1uA output current. The measurement result is shown in Fig. 6. The output current has a supply sensitivity of only 3% when the supply voltage changes from 3.3V to 2.3V. This supply sensitivity is much smaller than the one reported in [3], which is about 39%. As the supply voltage continues to decrease, the output mirror enters triode region, so the output current drops sharply. However, the 3nA reference current generator circuit itself is still in saturation region and generates a stable reference current.

**References**

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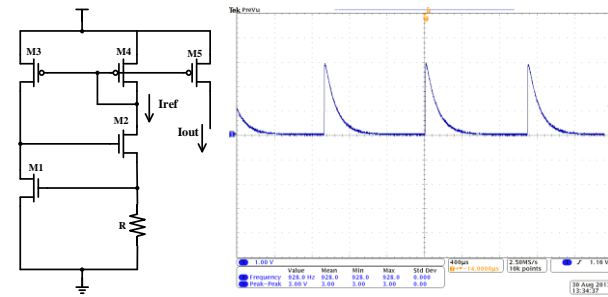


Fig. 1 Current reference circuit with off-chip resistor

Fig. 2 Oscillation of circuit in Fig. 1

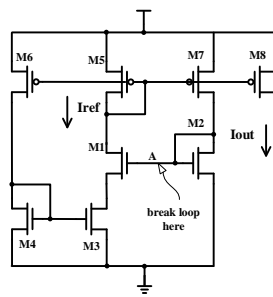


Fig.3 Current reference circuit using only transistors

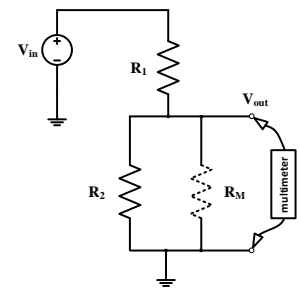


Fig. 5 Measurement of multimeter input resistance

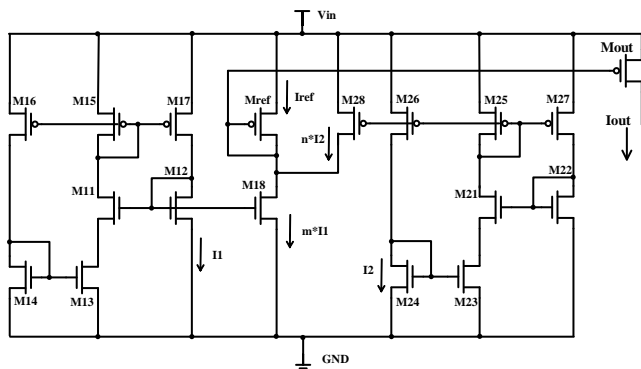


Fig. 4 Nano-ampere current reference circuit with reduced supply sensitivity

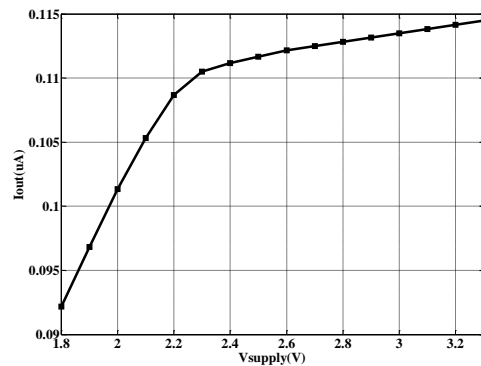


Fig. 6 Output current measurement result