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A simple and effective method to achieve the successful start-up of a current reference

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Abstract: Start-up design is a critical issue in current reference as it is very closely related to production yield. However, its function is difficult to predict using normal transaction simulations before the device is put into diffusion. In this paper, we discuss a simple and effective simulation approach which ensures a successful start-up process in a self-biased temperature independent current reference. The circuit is implemented in a class-D power amplifier with a 0.35 μm BiCMOS process and the experimental result validates that, by using this method, the start-up success rate can be greatly improved to 100%.

Key words: temperature independent current reference; bi-stable circuit; start-up process; simulation method; yield improvement

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1. Introduction

Current reference is key to providing a current bias for most analog integrated circuits, such as operational amplifiers (op-amp), comparators, digital-to-analog converters (DAC) or analog-to-digital converters (ADCs)[1]. The start-up circuit plays a very significant role in the current reference because the current reference is commonly implemented by a bi-stable circuit[2]. Several kinds of start-up techniques have been published in Refs. [3–5]. Their efforts all focus on how to achieve the start-up function with lower voltage, lower power dissipation or a faster response. However, by using a general simulation it is very hard to check whether the proposed start-up function works reliably. The effectiveness of the start-up process can only be evaluated by testing the fabricated device. In practice, the start-up problem is considered as one of the main factors that may reduce the yield of a design put into production. For cost reduction and yield improvement, an effective simulation method that ensures a successful start-up sequence is highly desirable.

In this paper, we propose a simple and effective method to analyze the start-up issue in a self-biased temperature independent current reference. The theoretical analysis of the start-up sequence is introduced, and the proposed simulation method to predict the start-up process is described.

2. Theoretical analysis

Generally, the precision of a current bias is not very important. However, in some special applications or special circuit structures, a precise bias such as a temperature independent current reference is required. Several methods have been proposed to obtain the temperature independent reference current[6–9]. In the commonly adopted ideas, the temperature independent current is composed of two branches: one is proportional to the absolute temperature (PTAT) and the other one is complementary to the absolute temperature (CTAT). A temperature independent current generated by a self-biased configuration is shown in Fig. 1. M1–M4 make up a self-biased configuration which ensures equal voltages on nodes A and B. Two resistors, R_2 and R_3, are parallel connected to the bipolar junction transistors (BJTs) Q1 and Q2, respectively. If R_2 is equal to R_3, the generated reference current $I_{\rm ref}$ can be expressed by Eq. (1).

$$I_{\rm ref} = (V_{\rm T}/R_1) \times \ln N + V_{\rm BE1}/R_2. \tag{1}$$

$V_{\rm BE1}$ is the emitter–base voltage of Q1, $V_{\rm T}$ is the thermal voltage, and N is the size ratio of Q1 and Q2 which is always set as 8 for layout matching. As we know, $V_{\rm BE}$ and $V_{\rm T}$ have opposite temperature coefficients. Choosing a pair of reasonable R_1 and R_2 can contribute to a zero temperature coefficient of $I_{\rm ref}$. By this means, a precise current $I_{\rm ref}$ which is independent of the temperature is generated.

As we know, a self-biased configuration is a bi-stable circuit which needs start-up trigger. In order to simplify our analysis, we choose the simplest, but not the best, start-up circuit, which is also shown in Fig. 1. When the circuit is powered on, M7, M8 and R_0 generate a current which is mirrored by M5 to be the start-up current $I_{\rm stup}$. $I_{\rm stup}$ will play a decisive role during the start-up process. The injected start-up current $I_{\rm stup}$ is divided into two branches, $I_{\rm Q1}$ and $I_{\rm R2}$, which are calculated in Eqs. (2) and (3). To trigger the self-biased configuration, $I_{\rm Q1}$ is the only effective section. However, $I_{\rm R2}$ has nothing to do with the start-up procedure.

$$I_{\rm Q1} = I_{\rm stup} R_2/(R_{\rm e} + R_2), \tag{2}$$

$$I_{R_2} = I_{\rm stup} R_{\rm e}/(R_{\rm e} + R_2). \tag{3}$$

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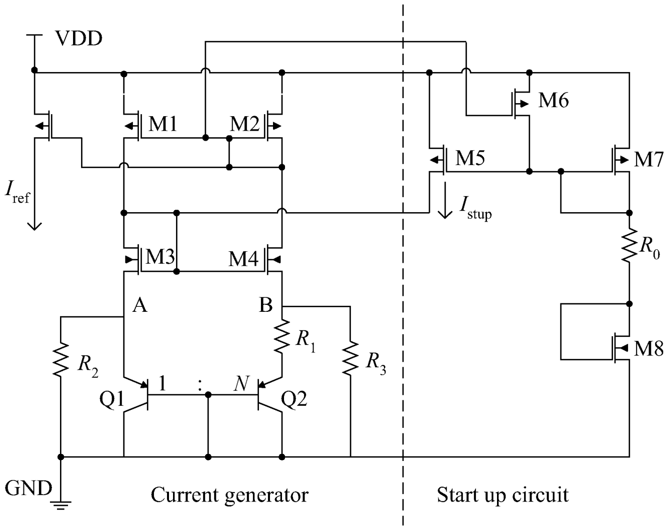

Fig. 1. The self-biased temperature independent current reference with a start-up circuit.

R_e is the equivalent emitter resistance of Q1, which can be calculated as:

$$R_e = V_T/I_e, \tag{4}$$

where I_e is the emitter current which is expressed as:

$$I_e = I_{sat}\exp[(V_{BE} - V_{BE0})/V_T]. \tag{5}$$

V_{BE0} and I_{sat} are the built-in voltage and the reverse saturation current of the PN junction, respectively.

From Eqs. (4) and (5), R_e is obtained as Equation (6) shows.

$$R_e = V_T\left[I_{sat}\exp(V_{BE} - V_{BE0})/V_T\right]^{-1}. \tag{6}$$

For BJT Q1, $V_{BE} = V_A$.

$$V_A = R_2 I_{R_2} = I_{stup}R_eR_2/(R_e + R_2). \tag{7}$$

If V_A is lower than V_{BE0}, R_e should be much higher than R_2. The current will flow into the lower impedance branch prior to the higher ones. So, I_{stup} firstly flows into R_2 rather than Q1. From Eqs. (2), (6) and (7), the effective start-up current I_{Q1} is obtained by Eq. (8).

$$I_{Q1} = \left\{V_T\exp[(I_{stup}R_eR_2/(R_e + R_2) - V_{BE0})/V_T] + R_2\right\}^{-1} \times I_{stup}R_2. \tag{8}$$

If I_{stup} is very small, there is no current flow into Q1 and the self-biased configuration cannot be triggered. If we increase I_{stup}, V_A will be increased. Consequently, R_e decreases and I_{Q1} increases. From the above analysis, it could be concluded that if I_{stup} is big enough to be injected to Q1, the self-biased structure can be started up. To ensure that the start-up function works successfully, I_{Q1} should not be lower than some tens of nA for the mismatching in diffusion. However, as we know, when the bi-stable circuit is started, the start-up current should be cut off to maintain balance. In Fig. 1, I_{stup} should be shut off by the feedback current of I_{ref} to isolate the start-up circuit from the current generator. If the feedback coefficient is suitable, there should be a compromised I_{stup} between the smallest current to start up the circuit and the biggest current to shut it down. The design of a reasonable I_{stup} is a very critical issue in this kind of circuit configuration.

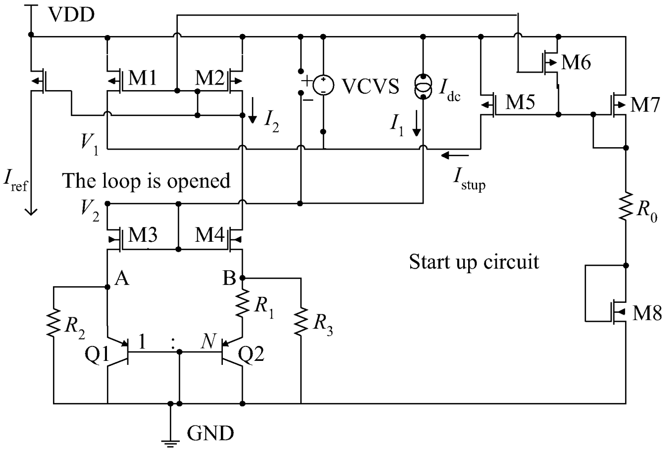

Fig. 2. Scheme of the proposed simulation approach.

3. Proposed simulation method for the start-up analysis

A simple and effective simulation method is proposed in this paper for designing a reasonable start-up current, I_{stup}, which is discussed by the complex calculation illustrated in Section 2. In our study, only the DC analysis is required to look for a reliable value of I_{stup}. First, we notice that the start-up circuit and the current generator that are shown in Fig. 1 constitute a close-loop configuration. With the injection of I_{stup}, Q1 and Q2 are triggered to arrive at the expected operating point, I_{ref}. At the same time, I_{ref} is mirrored by M6 as a feedback element to cut off the current I_{stup} in M5. For example, I_{Q1} is increased with the injection of I_{stup}, I_{ref} is also increased, accordingly. However, I_{stup} is decreased while I_{ref} is increased. It means that a start-up risk possibly occurs. To simplify this complex uncertain operating sequence, in this study, we will open this loop, as Figure 2 shows, to make the analysis of the start-up process more clear. I_1 is considered as the injected start-up trigger. A voltage control voltage source (VCVS) is a bias to make V_1 equal to V_2. It can be found that the circuit will present stabilization only when I_1 is equal to I_2. DC simulation is carried out by sweeping I_1. We observe the records on I_2 and I_{stup}. The simulation result is shown in Fig. 3.

Two stable regions are presented during DC operation. The first one is P1, where Q1 and Q2 are both in a cutoff state. This is an unexpected but stable operating point. The second stable region is only at point P2, which is the expected DC operating point to generate the current reference I_{ref}. At this time, the start-up function works successfully. The self-biased configuration is shown to be a bi-stable circuit. Without a successful start-up process, the circuit will work in region P_1. The criterion on whether the start-up function works effectively is that I_{stup} could inject a current high enough to trigger the bi-stable circuit to leave region P1 for point P2. However, I_{stup} should be shut down when the circuit arrives at P2, because the current

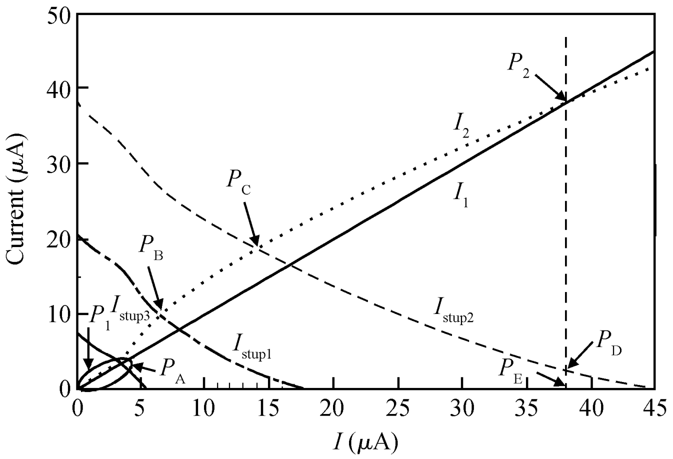

Fig. 3. Simulation results to evaluate the start-up currents.

generator should be isolated from the start-up circuit when the current reference works at its expected state.

As shown in Fig. 3, I_{stup1}, I_{stup2} and I_{stup3} depend on the three different values of R_0, which are equal to 100 kΩ, 30 kΩ and 250 kΩ, respectively. P_A is the crossing point of I_{stup3} and I_2. We can see that P_A is located in region P1, which means that I_{stup3} cannot provide a large enough start-up current to trigger the circuit to leave region P_1 for point P_2. There should be a start-up failure risk when R_0 is 250 kΩ. P_C is the crossing point of I_{stup2} and I_2, which is beyond P_1, so I_{stup2} can ensure a successful start-up sequence. However, when the circuit operating point is P_2, I_{stup2} arrives at point P_D, which is not zero but about 2 μA. It means that when the circuit works at the expected DC point, there is still 2 μA start-up current interfering with the balance of the self-biased structure. When R_0 is set as 100 kΩ, P_B, which is the crossing point of I_{stup1} and I_2, is higher than P_1. I_{stup1} can be considered as an effective start-up trigger. In addition, P_E drops to zero, which ensures the complete shutdown of the start-up current. So we can confirm that I_{stup1} is the expected value of the start-up current.

Focusing on this self-biased temperature independent current reference, the proposed simulation analysis is a very simple but effective method which can solve the complex start-up issue by adjusting R_0 to achieve a reliable start-up current. The other factor that can affect the start-up process is the feedback coefficient, which is determined by the ratio of M2 and M6. Similar analysis is already available to deal with the feedback coefficient and it will not be repeated in this work.

4. Experimental result

To validate whether the proposed method is reliable, a temperature independent current reference with the start-up circuit is integrated in a class-D power amplifier which is fabricated in 0.35 μm BiMOS technology.

Three versions of start-up circuit are implemented. In each version, R_0 is designed as 30 kΩ, 100 kΩ and 250 kΩ, respectively. The desired reference current I_{ref} is 40 μA, which could be evaluated on the test point placed by the layout design. We make use of an external resistor which is 30 kΩ to be the current sensor. For each version 50 samples are tested. Figure 4 shows the final results.

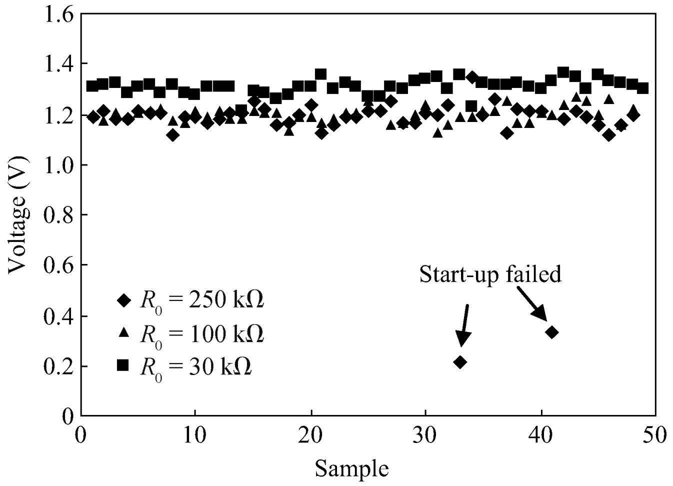

Fig. 4. Statistic diagram of the experimental results.

We can find that if $R_0 = 30$ kΩ, the measurement results are somewhat higher than the desired value because the start-up current is not shut down absolutely. However, for $R_0 =$ 250 kΩ, there are two investigated samples fail to start-up. We can choose $R_0 = 100$ kΩ as an optimal design to achieve a successful start up process for this current reference, because all samples in this case worked as we designed. This test result can greatly validate the simulation method which is proposed in Section 3.

5. Conclusion

In this paper, the start-up issue is discussed for the self-biased temperature independent current reference. A simple but effective method to achieve a successful start-up process by using an open loop DC analysis is proposed with the theoretical derivation and simulation verification. The experimental results validate that this approach is reliable and effective. This method is very easy to carry out and it can greatly improve yield before the design is put into production. It should be mentioned that the proposed method is available not only in the circuit referred to this paper but also in any other start-up structure using a feedback loop.

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