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Super current recycling folded cascode amplifier with ultra-high current efficiency

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ABSTRACT

An ultra-high current efficiency current recycling folded cascode amplifier is presented in this paper. To improve the current efficiency of conventional recycling folded cascode amplifier, it utilizes adaptive biasing class-AB input stage and local common-mode feedback techniques, leading to a boost in gain-bandwidth and slew rate. Both conventional and proposed recycling folded cascode amplifiers are designed on CSMC 180 nm process. Simulation results demonstrate that the proposed current recycling amplifier achieves 3.2 times the gain-bandwidth and 7.7 times the slew rate that of traditional counterpart with only 25% additional power consumption.

1. Introduction

In some applications such as switched-capacitor (SC) circuits or LDOs, the operational transconductance amplifiers (OTAs) demand fast settling time, which require wide gain-bandwidth (GBW) and large slew rate (SR) [1]. The conventional folded cascade amplifiers (FC) are the most commonly used in the amplifier structures [2]. However, due to its operating at class-A, the current efficiency (CE) is not large enough. Recent years, the current recycling folded cascode amplifier (RFC) gets preferred over the traditional FC owing to the improved GBW and SR [3,4]. However, since the tail current of the input differential pairs and the ratio factor of current mirror are limited, the GBW and SR of RFC cannot achieve the larger values. Recently, some techniques, such as current-shunt, positive-feedback and double-recycling, have been proposed to further improve the GBW and SR of RFC [5–8]. Although these presented techniques have enhanced the GBW and SR of RFC, the transconductance and achievable maximum output current are still linearly increased with the tail current of input pairs, which severely constrains the achievable CE.

In this paper, a proposed super current recycling folded cascode amplifier with enhanced CE is presented. By employing the adaptive biasing class-AB input stage formed by the cross-coupled flipped voltage followers (FVFs) [9–11] and the local common-mode feedback (LCMFB) [9,10] current mirrors for the conventional RFC, not only has the GBW been improved, but also the maximum output current for slewing is proportional to V_{in}^4, leading to the improvement of CE compared to the traditional counterpart.

The following sections present the details of the proposed super recycling OTA. In Section 2, we summarize the CE of the conventional RFC. In Section 3, we propose each technique details and the detailed circuit analysis are discussed. The performance comparisons, the traditional RFC and the proposed super recycling structure, are given in the Section 4. The Section 5 gives the conclusions.

2. The CE of traditional RFC

The traditional RFC is shown in Fig. 1 [3,4], and then the equivalent transconductance (G_m) can be expressed as,

$$G_{m,RFC} = (1 + K)g_{m,1a} \tag{1}$$

where $g_{m,1a}$ is the transconductance of input pairs $M1a$. Accordingly, the GBW can be given as,

$$GBW_{RFC} = \frac{G_{m,RFC}}{C_L} \tag{2}$$

Also, the slew rate can be described as,

$$SR_{RFC} = \frac{2KI_B}{C_L} \tag{3}$$

where K is the ratio factor of current mirror. To keep power consumption unchanged compared to FC, the value of K is often chosen to be 3. Therefore, the GBW and slew rate of RFC are twice and three times that

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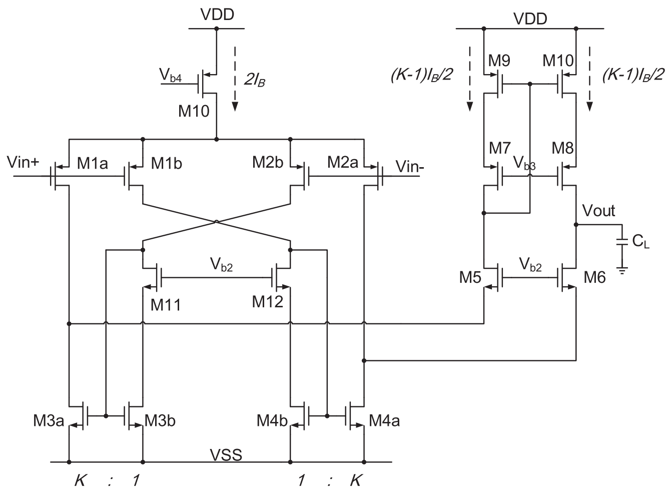

Fig. 1. The traditional RFC.

of FC with unchanged power dissipation.

Usually, FoM_S and FoM_L are used to evaluate the current efficiency of an OTA, which is expressed as $FoM_S = 100 \cdot GBW \cdot C_L/I_{tot}$ and $FoM_L = SR \cdot C_L/I_{tot}$. Therefore, the FoM value for RFC can be given as,

$$FoM_{S,RFC} = 100 \cdot \frac{(1+K)g_{m,1a}}{4I_B} = 100\frac{g_{m,1a}}{I_B} \tag{4}$$

$$FoM_{L,RFC} = \frac{2KI_B}{4I_B} = 1.5 \tag{5}$$

Note that the CE of RFC is not large enough. Especially for the large signal response, the FoM_L value is constant.

3. Super recycling folded cascode amplifier

To further improve the CE of the RFC, we propose a super current recycling folded cascode amplifier (SRFC), shown in Fig. 2, which utilizes the adaptive biasing class-AB input stage to substitute the original tail current source and the proposed local common-mode feedback current mirror to replace the traditional current mirror.

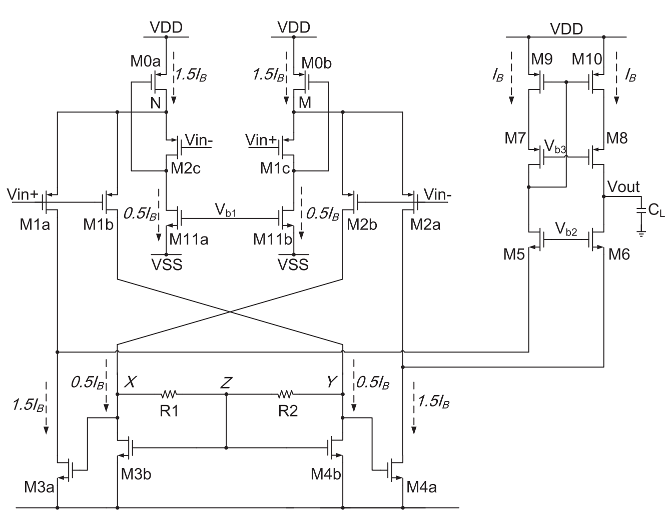

Fig. 2. The proposed super recycling folded cascode amplifier (SRFC).

3.1. Circuit description

The input differential pairs $M1a(b)$ and $M2a(b)$ are cross-coupled by two FVFs, which consists of the matched input transistors $M2(1)c$, diode-connected transistors $M0a(b)$ and current source transistors $M11a(b)$. Meanwhile, the active current mirrors in the RFC are replaced by the local common-mode feedback circuits composed of matched resistors $R1(2)$. In dc quiescent conditions, the dc currents flowing through input pairs $M1a(b)$ and $M2a(b)$ are set by the current source $M11a(b)$, which is $0.5I_B$ as that of RFC. Owing to no current flowing through resistors $R1$ (2), the voltage at node X (Y) and Z are equal. Therefore, the size ratio $(W/L)_{3a}/(W/L)_{3b}$ of current mirror $M3a$: $M3b$ determines the dc current through them. To maintain the same power, it is chosen to be K as that of RFC. Owing to additional dc current of $M11a(b)$, the total bias current of SRFC is increased to $5I_B$.

3.2. The GBW

Owing to the cross-coupled FVF in the input stage, the ac input signal is also applied to the source terminal of $M1a(b)$ and $M2a(b)$. Meanwhile, since the node Z is virtual ground, the equivalent transconductance G_m of SRFC can be described as,

$$G_{m,SRFC} = 2(1 + g_{m,3a}R_1)g_{m,1a} \tag{6}$$

Accordingly, the GBW of SRFC can be expressed as,

$$GBW_{SRFC} = \frac{G_{m,SRFC}}{C_L} \tag{7}$$

Note that if a large value of $R1$ is chosen, $g_{m3a}R_1$ would be larger than K in RFC. Therefore, the enhancement of G_m is obtained compared to RFC at the same power. Accordingly, a boost in GBW is also achieved.

3.3. DC gain

The dc gain (A_v) of an OTA can be described as,

$$A_v = G_m \cdot R_{out} \tag{8}$$

where R_{out} is the equivalent output resistance of an OTA. Owing to the nonzero output resistance of the FVF, the node M and N can not be considered as the ac ground. Thus, we analyze the output resistance at drain terminal of $M2a$, shown in Fig. 3(a), and the equivalent circuit is shown in Fig. 3(b). The output resistance (R_o) can be given as,

$$R_o = \frac{V_X}{I_X} \approx r_{ds,1a} + \frac{1}{g_{m,0a}} \approx r_{ds,1a} \tag{9}$$

where r_{ds} is the output resistance of the transistors. Then the R_{out} of SRFC can be expressed as,

$$R_{out} \approx [(g_{m,8}r_{ds,8})r_{ds,10}] \| [(g_{m,6}r_{ds,6})(r_{ds,4a} \| r_{ds,1a})] \tag{10}$$

Note that although the output resistance of the SRFC is almost the same as that of traditional RFC, the dc gain is also enhanced due to the improved G_m.

3.4. Slew rate

To analyze the large signal response, we assume that a large negative step signal ΔV is applied to $Vin+$, the voltage at node M rapidly decreases, making the input transistors $M2a$, b turned off. Then the voltage at node X decreases, making transistor $M3a$ cut off, and consequently the input transistor $M1a$ goes into triode region. Owing to the effect of the FVF, voltage at node N keeps constant. Therefore, the current I_{in} flowing through $M1b$ is not limited by the quiescent tail current $1.5I_B$, which increases with the input signal and can be expressed as,

$$I_{in} = \frac{\beta_{1b}}{2}(\sqrt{\frac{I_B}{\beta_{1b}}} + \Delta V)^2 \approx \frac{\beta_{1b}}{2}\Delta V^2 \tag{11}$$