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A Design of Gain Boosted Error Amplifier Applied to PWM Control

Yu Shi-Hua[1], Wang Kai-Yu*[2], Wei Shu-Ping[2], Wang Xiao-Feng[2], Yang Ming-Jian[2]
[1]School of Computer Science and Technology, Hulunbuir University,
Hulunbeier, 021008, China
[2]School of Electronic Science and Technology, Dalian University of Technology,
Dalian, 116023, China
*Corresponding author, e-mail: wkaiyu@dlut.edu.cn

Abstract

A high gain, wide common-mode and high swing error amplifier is proposed. It can be applied to a PWM control chip. The error amplifier adopts folded cascode structure with gain boosted. This chip is simulated and fabricated in the CSMC 0.5μm CMOS. The result shows that the error amplifier has the DC gain of 141.11dB, the common-mode input range of 0~3.87v and the output swing of 0.11~4.80v. These meet the requirements of engineering applications and can realize stable system output.

Keywords: *PWM controller, folded cascode amplifier, gain boosted, error amplifier*

1. Introduction

With the rapid development of electronic technology, the relationship between electronic products and people's lives is increasingly close. Almost all electronic products are related to the power management, so power management market is also directly influenced by the production of electronic products. Furthermore, switching power supply technology is also in constant innovation. This provides a broad space for development of switching power supply. PWM control chip is the core of the power regulator, and error amplifier is a vital component in the chip. Error amplifier's output swing directly determines the maximum and minimum value of the output duty cycle of the PWM chip. The fixed output swing make the maximum, minimum value of chip output duty ratio cannot be adjusted. What is more, it limits the application of the chip and affects the performance of the PWM chip.

Based on the requirements of the entire chip, we put forward a high-performance error amplifier which have high-gain, wide common-mode input range and output swing. This circuit adjusts the duty cycle of the pulse signal by amplifying the difference between the feedback voltage and the reference voltage to achieve the purpose of stabilizing the output voltage.

2. The Circuit Structure and Working Principle

2.1. Error Amplifier Circuit

The function of the error amplifier magnifies the difference between the feedback voltage and the reference voltage. The amplified result, connecting the PWM comparator positive phase side input, compare with the ramp voltage. The result of the comparison is used to control chip output duty cycle of the PWM signal ratio so as to control the time of switch on and off. Finally, it keeps the output voltage stable. It is a key component of the chip.

2.1.1. The Analysis of Gain Boosted Principle

The folded cascode structure improves CMIR comparing to the rest of the op-amp structure. The upper limit of the common mode input range is the same with the upper limit of the basic two stage operational amplifier and telescopic cascode amplifier. On the other hand, if the value of V_BIAS can meet the M_9 and M_{10} operating in the linear region, it can significantly lower the common-mode input threshold. But in actual cascode circuit, power supply voltage and the signal swing requirements limited amplifier's stage. In order to increase the gain, we can be used to add a bootstrap circuit. Using a gain bootstrap circuit, we can effectively

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increase the output resistance of cascode circuit. As shown in Figure 1, it is the structure of the bootstrap cascode amplifier.

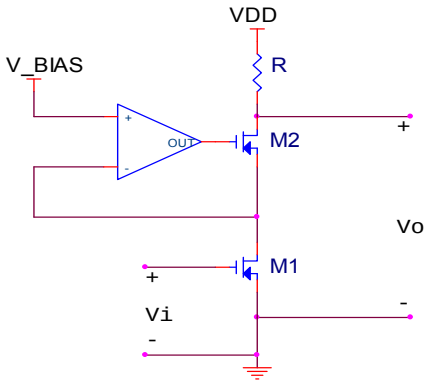

Figure 1. Cascode Structure Circuit with Gain Boosted

This circuit uses an amplifier as a negative feedback loop to control the voltage between the transistor M_2's gate and ground. If the gain of the amplifier is infinite, the negative feedback loop can adjusted gate voltage of M_2 until the two input voltage difference of the amplifier is zero. In other words, the drain-source voltage of the transistor M_1 can be adjusted to close to V_BIAS. If the drain-source voltage of M1 keeps constant, the change of the leakage current has no impact on the output voltage. Besides, the output resistance is close to infinity. In actual circuit, the gain of the amplifier is a limited value, which means that the drain-source voltage of M_1 is not a constant value and the output resistance is also a finite value. Then, analyze the small-signal model of the circuit through the Figure 2.

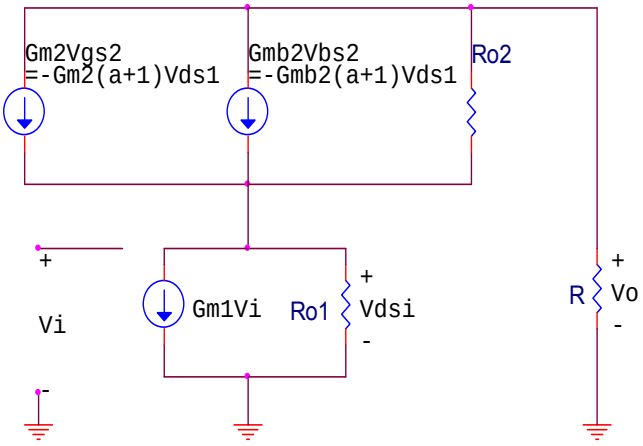

Figure 2. The small signal model of cascode structure with gain boosted

From the qualitative point of view, the leakage current of M_2 increase when the output voltage increasing. Thus it increase the leakage current and the drain-source voltage of M_1. Drain source voltage increase through the amplifier with the -α magnification. This decreases the voltage between the gate and ground of the M_2. The decrease of the gate voltage of M_2 lead to the leakage current's decrease. This enlarges the output resistance, comparing to the ordinary cascode structure. The role of feedback can make the gate voltage of M_2 keeps constant.

Figure 3 shows a small-signal equivalent circuit diagram of the cascode structure with the structure of the bootstrap circuit in low frequencies. The transistor M1 was modulated by body effect transconductance. The drain-source voltage of M_2 for:

$$V_{gs2} = V_{g2} - V_{s2} = V_{g2} - V_{ds1} = -\alpha V_{ds1} - V_{ds1} = -(\alpha + 1)V_{ds1} \quad (1)$$

However, in the usual cascode structure, M2 of the gate-source voltage is $V_{gs2} = -V_{ds1}$. If α >0, comparing to the common cascode structure, the factor of equation (1) have amplified action. It is the core of bootstrap type cascode structure.

Since usually the only difference between cascode structure of M_2 and bootstrap cascode structure in small signal model is the different V_{gs2}. The V_{gs2} affects only through the current of transconductance g_{m2}. When analysis the bootstrap cascode circuit, we only make the original common-source common-gate structure g_{m2} convert into $(\alpha+1)g_{m2}$. In other words, the bootstrap cascode circuit can be seen as a cascode circuit that g_{m2} become large. So a bootstrap cascode amplifier transconductance is:

$$G_m = g_{m1}\left(1 - \frac{1}{1 + [g_{m2}(\alpha + 1) + g_{mb2}] + \frac{r_{ds1}}{r_{ds2}}}\right) \quad (2)$$

Similarly, in general there is $Gm \approx g_{m1}$. Therefore, bootstrap circuit not need to change the transconductance.

The structure of bootstrap cascode reduces the source resistance R_{i2} of M_2 when compared with the usual structure of cascode. This reduce the ratio of the drain-source voltage of transistor M_1 (V_{ds1}) to the output voltage (Vo), thereby increasing the output resistance. The g_{m2} in Cascode formula is replace by $(1+\alpha)g_{m2}$. Then we obtain the common gate of source bootstrap circuit resistance value:

$$R_0 = r_{ds1} + r_{ds2} + [g_{m2}(\alpha + 1) + g_{mb2}]r_{ds1}r_{ds2} \cong [g_{m2}(\alpha + 1) + g_{mb2}]r_{ds1}r_{ds2} \quad (3)$$

Compared with ordinary cascode amplifier, output resistance of bootstrap cascode circuit is about $[g_{m2}(\alpha+1) + g_{mb2}]$ rds1 times the normal level.

2.1.2. The Circuit Design of Gain Boosted Amplifier

We add four OpAmp on the basic cascode amplifier to form the bootstrap circuit and amplifies the gain. The gates of M_5, M_6, M_7 and M_8 don't directly connect with the four bias voltages, but connecting the output of the four operational amplifiers. While the four amplifiers making up a negative feedback loop increase the resistance, when we see from the drain of a transistor.

Such as expressed in equation 3, the bootstrap circuit can increase the output resistance, so that the output transconductance of the transistor increases (α+1) times, which α is the gain of bootstrap operational amplifier. Due to the different bias voltage, we make the gain of auxiliary amplifier at M_5 and M_6 is A_1, and get Figure 3.

The improved with bootstrap circuit cascode structure amplifier

$$R_{out|M6} = r_{ds4} + r_{ds6}\{1 + [g_{m6}(A_1 + 1) + g_{mb6}](r_{ds4})\} \cong (A_1 + 1)(g_{m6}r_{ds4})r_{ds6} \quad (4)$$

Let the gain M_7 and M_8 for is A_2

$$\begin{aligned} R_{out|M8} &= (r_{ds2} \| r_{ds10}) + r_{ds8}\{1 + [g_{m8}(A_2 + 1) + g_{mb8}(r_{ds2} \| r_{ds10})\} \\ &\cong (A_2 + 1)g_{m8}(r_{ds2} \| r_{ds10})r_{ds8} \end{aligned} \quad (5)$$

Based on the above two type can obtain the resistance of circuit output:

$$R_o = (R_{out|M8}) \| (R_{out|M6}) \quad (6)$$

Calculate the gain was:

$$A_V = G_m R_o \quad (7)$$

As can be seen from the above two formulas, the overall gain of the circuit becomes large, we achieve gain bootstrap effect.

3. Circuit Simulation and Test

Get Table 1, comparing to folded cascode circuit. From the results in Table 1 can be seen, the gain of the gain bootstrap amplifier improves obviously when compared with the gain of basic amplifier, output power also increased significantly. At the same time, it doesn't have influence on the other performance indicators of the amplifier. The final design results meet the requirements (Figures 3 and 4).

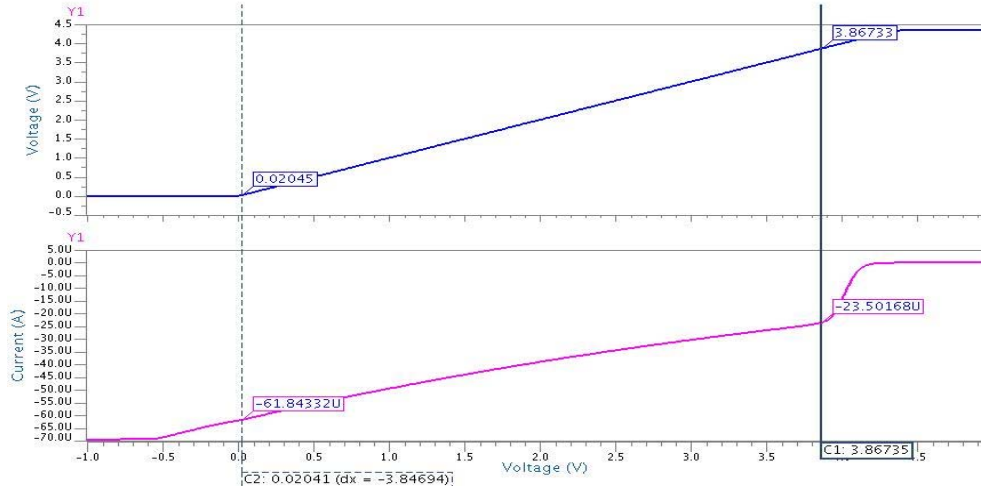

Figure 3. Simulation result of gain and bandwidth of gain boosted amplifier

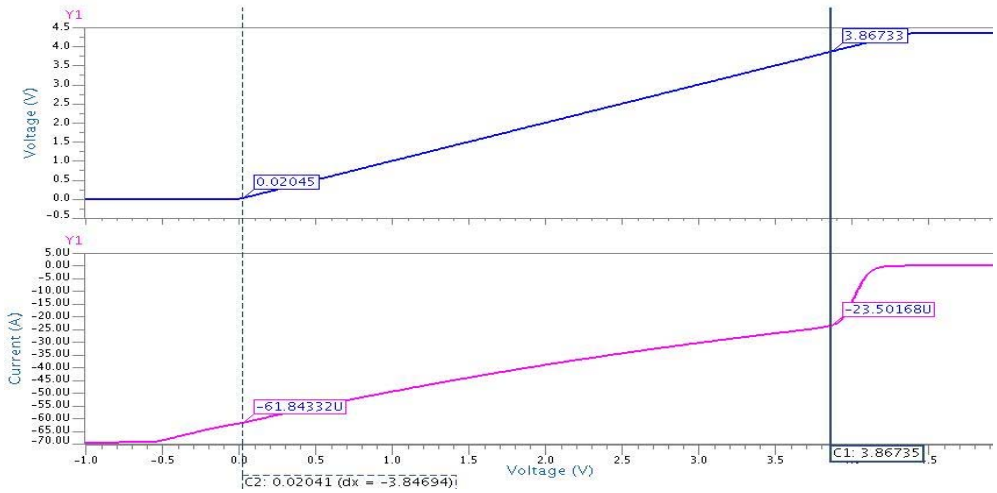

Figure 4. Simulation result of CMIR of gain boosted amplifier

Table1. The comparison of basic model's and gain improve model's simulation result.

Simulation items	Basic amplifier	Gain boosted amplifier
AV	98.90dB	141.4dB
GBW	23.71MHz	20.68MHz
ICMR	0~3.93V	0~3.87V
Output Swing	0.16~4.8V	0.11~4.80V
CMRR	122.85 dB	117.88dB
SR	+14.61V/μs,-38.55V/μs	+13.301V/μs, -43.04V/μs
Setup time	109.56ns	119.39ns
PSRR	84.33dB	94.6 dB
Power Consumption	9.72mW	18.84 mW

4. Circuit Layout and Chip Test

Figure 5 for this paper design gain bootstrap error amplifier used in PWM control chip to realize the layout. The layout structure meets minimum Area requirements, considering the matching, symmetry and so on. Finally, it successfully taped out in CSMC 0.5um DPDM mixed signal process. Using Agilent E3641A power supply, Agilent 33520 gives a signal, placing signage at Tektronix TDS2022 oscilloscope and Fluke 15 b digital multimeter to test chip. Test result: output voltage is 1.5805V, a error of 0.5 mV, ripple of 3mV after the system steady (as shown in Figure 6: the curve amplification chart after the system stable output).

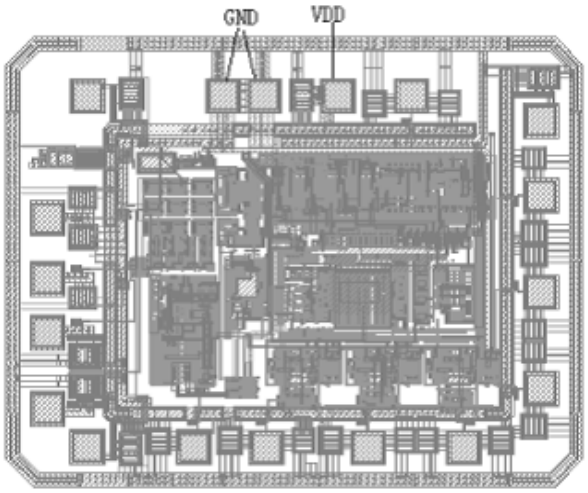

Figure 5. Layout of whole chip

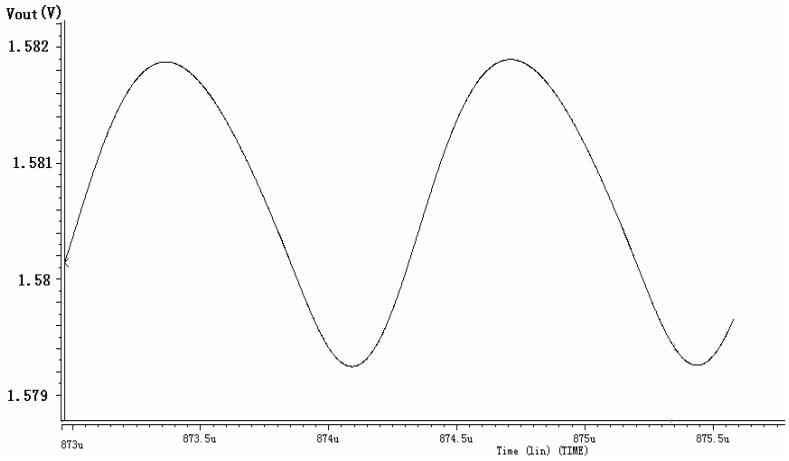

Figure 6. The output curve of Vout

5. Conclusion

This paper design a high performance gain bootstrap error amplifier with high gain, wide common-mode input range and swing. Spice simulation shows that, compared with the basic error amplifier, in the case of other properties change little gain has been greatly improved. But the corresponding power consumption doubled. Through chip test, the PWM control chip performance is good.

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