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A New Structure for a CMOS Audio Power AMP with Extremely Low THD and Low Power Consumption*

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Abstract: A new system-corrected CMOS audio power AMP is presented. Consisting of four single-end OPAs, this structure is a pseudo-differential system. Compared to conventional CMOS power AMPs, it has the merits of low power consumption, extremely low THD, easy compensation, and good driving capability. With 1st silicon 0.25μm 1P4M CMOS technology and a 3V power supply, the output range can be 4Vpp when driving an 8Ω ‖300pF load, while its power dissipation is less than 3mW. The THD is better than 0.003% at 1kHz. A new over-current protection circuit, which can effectively protect the power output circuits on the chip, is also demonstrated.

Key words: system-corrected structure; CMOS power AMP; over-current protection
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1 Introduction

With the continuing development of high quality portable terminals, the requirement of high quality audio power amplifiers (AMPs) is becoming more popular. An audio power AMP requires the characteristics of low power consumption, low total harmonic distortion (THD), a large dynamic range, and a large driving capacity. Thus, it is a big challenge to design a CMOS audio power AMP.

According to the feedback theory equation, $THD_{CLOSED} = THD_{OPEN} \frac{1}{1 + A(\omega) F}$ [1], increasing the loop gain, especially the open loop gain $A(\omega)$, is the most effective method. Generally, due to power supply limitations, a multi-stage OPA is chosen. However, with more stages, there are more poles, which induce stability issues.

Hwang and Lee[2] contrived an adaptive Q-current controlled class AB structure that can effectively decrease cross-over distortion. However, the structure is very complicated and consumes large current.

Brigati and Francesconi[3] adopted the pseudo source follower structure. They used a Pre AMP and an Error AMP to increase the open loop gain. The Error AMP plus the output stage MOS constituted the pseudo source follower structure. Since an offset exists, the gain of the Error AMP is no more than 10[4,5], which contributes little to improve the THD.

Pernici *et al*.[6] proposed a four-stage cascaded structure to increase the open loop gain. In order to solve the stability problem, the Nested Miller Compensation was adopted. Though the open loop gain has been dramatically improved, a complicated compensation method and huge capacitor have also been introduced. Moreover, for the limited gain band width product (GBW), the THD has not been improved greatly.

Recently, Fujimoto *et al*.[7] used a sigma-delta technique to realize an audio power AMP, and Forejt *et al*.[8] designed a CLASS D audio AMP with 90nm technology. Excellent THDs have been achieved with their circuits. However, both of them require a high precision clock and costly external inductance.

A new system-corrected CMOS audio power AMP will be presented in this paper. It provides extremely high open loop gain with a simple structure and a negative zero to compensate the pole

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effects and enhance the systematic phase character. When it is used to drive an 8Ω ‖300pF load, the output voltage range can exceed 4Vpp with 3V supply voltage. The static dissipation is less than 3mW, and the THD is better than 0.003%. The structure of the system-corrected CMOS audio AMP will be described in detail, and a die photograph and the test results will also be presented.

2　Structure of the system-corrected power AMP

2.1　Theory of the system corrected power AMP

Consider the structure in Fig. 1. The signal source V_i is connected to the positive terminal of the AMP. Assuming that the signal source is ideal

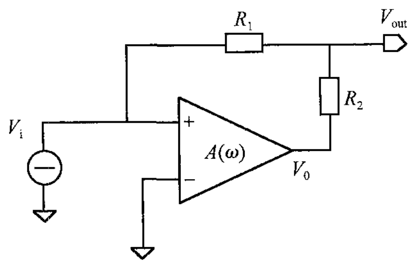

Fig. 1　Pre AMP of the system-corrected structure

(inner resistor is zero), we get

$$V_0 = A(\omega) V_i \quad (1)$$

$$V_{out} = (V_0 - V_i)\frac{R_1}{R_1 + R_2} + V_i \quad (2)$$

Combining Eqs. (1) and (2), we get

$$H(\omega) = \frac{V_{out}}{V_i} = \frac{R_1}{R_1 + R_2}(A(\omega) - 1) + 1 \quad (3)$$

where $A(\omega)$ is the open loop gain of the AMP. When $A(\omega) \gg 1$,

$$H(\omega) = \frac{V_{out}}{V_i} \approx \frac{R_1}{R_1 + R_2} A(\omega) \quad (4)$$

When $A(\omega) \ll 1$, Equation (3) becomes

$$H(\omega) = \frac{V_{out}}{V_i} = \frac{-R_1}{R_1 + R_2} + 1 = \frac{R_2}{R_1 + R_2} \quad (5)$$

Assuming that the AMP has only one pole p_1, then

$$A(\omega) = \frac{A_0}{1 + \frac{s}{p_1}} \quad (6)$$

Substituting Eq. (6) into Eq. (3), we get

$$H(\omega) = \frac{V_{out}}{V_i} = \frac{R_1}{R_1 + R_2}\left(\frac{A_0}{1 + \frac{s}{p_1}} - 1\right) + 1$$

$$= \frac{R_1\left(A_0 - \left(1 + \frac{s}{p_1}\right)\right) + (R_1 + R_2)\left(1 + \frac{s}{p_1}\right)}{(R_1 + R_2)\left(1 + \frac{s}{p_1}\right)} \quad (7)$$

Setting the numerator of Eq. (7) to zero, we get

$$s = -A_0 p_1 \frac{R_1}{R_2} = -\omega_0 \frac{R_1}{R_2} \quad (8)$$

where ω_0 is the unity gain bandwidth. Equation (8) shows that a negative zero ω_z has been introduced in the path of R_1 and R_2.

$$\omega_z = -\omega_0 \frac{R_1}{R_2} \quad (9)$$

With this structure, a closed loop AMP has been connected to its output, and the system-corrected power AMP comes into being. For the sake of simplicity, the left AMP is named AddAmp, and the right AMP is named MainAmp. Figure 2 shows the unity feedback structure of the system-correc-

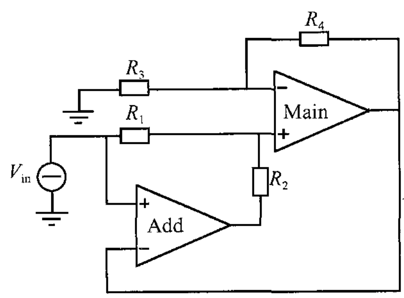

Fig. 2　Unity feedback structure of the system-corrected power AMP

ted power AMP. When the gain of MainAmp ≫1, the open loop transfer function of the system corrected power AMP is

$$A_S(\omega) = H_A(\omega)\left(1 + \frac{R_4}{R_3}\right) \quad (10)$$

Here $H_A(\omega)$ represents the transfer function of AddAmp. The nonlinear distortion of the system-corrected power AMP mainly occurs in MainAmp. With the path of R_3 and R_4, the THD of MainAmp is

$$THD_M = \frac{THD_{OPEN\_M}}{1 + A_M(\omega) F_M} \quad (11)$$

where $A_M(\omega)$ is the open gain of the MainAmp, F_M is the feedback coefficient of the MainAmp, and THD_{OPEN_M} is the open loop THD of the MainAmp. According to Eqs. (10) and (11), the closed unity feedback THD of the system corrected structure is

$$THD_{CLOSED\_S} = \frac{\dfrac{THD_{OPEN\_M}}{1 + A_M(\omega)F_M}}{1 + A_S(\omega)F_S}$$

$$= \frac{THD_{OPEN\_M}}{\left(1 + A_M(\omega)\dfrac{R_3}{R_4 + R_3}\right)\left(1 + H_A(\omega)\left(1 + \dfrac{R_4}{R_3}\right)\right)} \quad (12)$$

When $A_M(\omega)F_M \gg 1$, $A_A(\omega) \gg 1$, substituting Eq. (4) into Eq. (12) yields

$$THD_{CLOSED\_S} \approx \frac{THD_{OPEN\_M}}{A_M(\omega)A_A(\omega)\left(\dfrac{R_1}{R_2 + R_1}\right)} \quad (13)$$

Equation (13) shows that the closed loop THD is dramatically decreased with the introduction of the AddAmp. The AddAmp also introduces a negative pole and a negative zero. Assuming that the open loop unity bandwidth of MainAmp is ω_{0M}, the dominant pole of the MainAmp is

$$\omega_{pM1} = \omega_{0M} F = \omega_{0M} \frac{R_3}{R_3 + R_4} \quad (14)$$

If the negative zero of the AddAmp cancels the dominant pole of the MainAmp, the system-corrected AMP will have just two poles. One is the dominant pole of the AddAmp, ω_{pA}, and the other is the second pole of the MainAmp, ω_{pM2}. That is,

$$\omega_{zA} = \omega_{pM1} = \omega_{0M} \frac{R_3}{R_3 + R_4} \quad (15)$$

According to Eqs. (9) and (15), the unity gain bandwidth of the AddAmp is

$$\omega_{0A} = \omega_{0M} \frac{R_3}{R_3 + R_4} \times \frac{R_2}{R_1} \quad (16)$$

Combining Eqs. (13) and (16), when $R_2 \gg R_1$ and $R_3 \gg R_4$, the THD of the closed loop reaches its minimum value. However, under the limitation of the output range of the AddAmp and the common mode input range of the MainAmp, we adopt $R_3 = 2R_4$, $R_2 = R_1$ in practice.

In the above analysis, the inner resistor of the signal source has been set to zero. However, this is not true in fact. When the resistor value is bigger than $\frac{R_1 + R_2}{A_A(\omega)}$, a positive feedback is produced in the AddAmp, which makes the system corrected power AMP less stable. Fortunately, a driving AMP with a low output resistor (a few ohms or tens of ohms) is often added before the power AMP. To keep the stability, the values of R_1 and R_2 must be several hundred kiloohms. In addition, increasing ω_{0M} can decrease the closed loop THD of the system. However, the load capacitor of the MainAmp is often several hundred pico-farads. In this case, it is difficult to enlarge ω_{0M}, and the consumed power will be very high.

In fact, Equation (15) is difficult to realize with the effects of temperature and the variety of the technology. To guarantee the stability of the system, we adopt the following condition:

$$\omega_{pM1} < \omega_{zA} < \omega_{pM2} \quad (17)$$

A floating current source structure[9] has been chosen to realize the MainAmp, which can effectively control the static current and provide a large dynamic current. The unity bandwidth of the MainAmp is about 1MHz, with a differential 300pF capacitor load. The DC gain is 110dB, and the phase margin is about 60°. Since the load capacitor of the AddAmp is small, it is easy to design an AddAmp with low power dissipation. A simple cascode structure has been used in this design. The DC gain of the AddAmp is over 80dB, and the unity bandwidth is about 500kHz.

2.2 Over-current protection circuit

Usually, an audio power AMP is used to drive a small resistor load, so it must have a good driving capacity. If the output of the power AMP is shorted to ground, the output MOS transistor will be damaged. Hence, an over-current protection circuit is necessary. Traditionally, a small resistor is placed in series with the output MOS transistor to limit the current, but this dissipates much power in the normal mode. A new structure for an over-current protection circuit is shown in Fig. 3. The output current is attenuated by the mirror circuit M1/M3 and M6/M7. When the current of the output transistors is large enough, the voltage of point A will drop to push the inverter change, and then transistors M2 and M4 will be closed while M1 and M5 will be cut off. Thus the output current is cut down. At the same time, the output of the INV3 is ‘high’, which sets the transistor M8 and shorts point A to the output. If the short ground path is not moved away, the over-current protection circuit will still work in the cut down mode. Once the short ground path is removed, the voltage of point A will rise immediately to push the inverter change, and the transistors M2 and M4 will be cut off. Then the output of INV3 will be ‘low’, and the system will return to the normal mode. The threshold of the protection current can be set by adjusting the value of resistor R and the width and

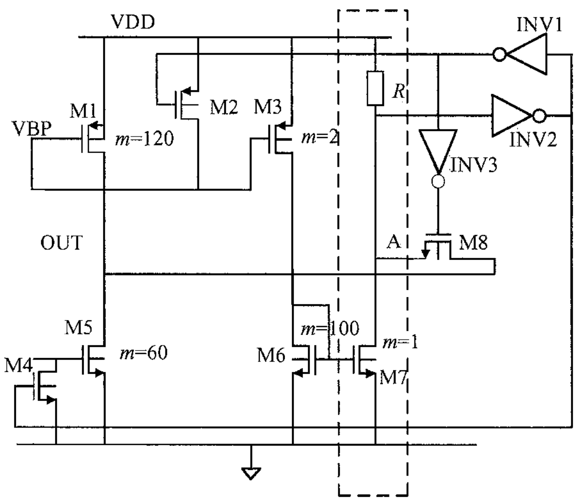

Fig. 3　Over-current protection circuit

length of the transistors in INV2. The over-current protection circuit of M5 is very similar to that of M1, which is not mentioned here.

3　Photograph of the die

Figure 4 shows a die photograph of the system-corrected CMOS audio power AMP. It occupies 0.48mm^2 and has been fabricated with 0.25μm 1P4M technology in 1st silicon.

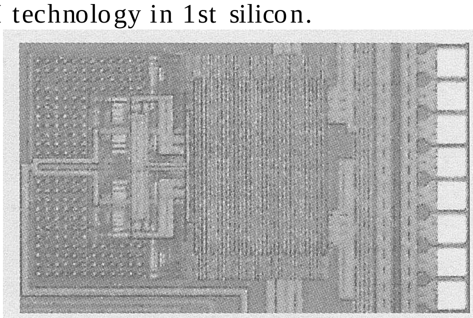

Fig. 4　Die photograph

4　Test results

Ten samples have been tested with the THD analyzer DF4120. The THD parameter is better than 0.003% with an 8Ω ‖300pF differential load and a 1kHz, 4Vpp sine wave stimulus. The average static current of the samples is 890μA. When the output terminal is shorted to ground, the current of the system-corrected CMOS audio power AMP decreases to 560μA. Once the short-to-ground line is removed, the AMP returns to the normal state. This provides strong evidence for the function of the new over-current protection circuit. The parameters are listed in Table 1. For comparison, the parameters of other power AMPs are listed in Table 2.

Table 1　Parameters of the system-corrected CMOS power AMP

	Average of the ten samples
Static current	890μA
Input offset voltage	1.6mV
Current of short-to-ground connection	560μA
SNR	> 100dB 1)
THD @1kHz 4Vpp 8Ω ‖300pF load	< 0.003% 2)
Maximum efficiency @2.5V power supply, THD < 0.003%	70%
PSRR @DC	120dB
Minimum supply voltage	1.5V

1) 100dB is the maximum value that can be detected by DF4120.
2) 0.003% is the minimum value that can be detected by DF4120.

Table 2　Parameters of the system-corrected power AMP and the other power AMPs

	System-corrected power AMP	Adaptive Q-current controlled class AB[2]	Class D[8]	Sigma-Delta switching power AMP[7]
Supply voltage/ V	3	5	4.2	5
Static power/ mW	2.7	13	7	300
THD @1kHz	< -90dB R_L = 8Ω	-54dB R_L = 8Ω	< -90dB R_L = 8Ω	-96dB
Area/ mm^2	0.48	2.88	0.44	12.6^2

5　Conclusion

A new system-corrected power AMP has been presented on the basis of analyzing the traditional power AMP. It has the merits of low power consumption, extremely low THD, easy compensation, and good driving capability. With a 1kHz 4Vpp sine wave stimulus, the THD is better than 0.003% when driving an 8Ω ‖300pF load. It consumes only 2.7mW of static power. A new over-current protection circuit has also been mentioned, which is very suited for the CMOS power AMP. Furthermore, it can detect an external short-to-ground circuit and manage with the right function automatically.

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一种新型的超低 THD,低功耗 CMOS 音频功率放大器*

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摘要: 提出了一种新型的系统矫正结构 CMOS 音频功率放大器. 该放大器是由 4 个单端运放组成的伪差分结构. 相对于传统的 CMOS 功率放大器, 它具有低功耗、超低 THD、易于补偿、驱动能力强等优点. 采用 1st silicon 0.25μm 1P4M 工艺制备, 在 3V 电源电压下, 驱动 8Ω ‖300pF 的负载, 其输出摆幅可以达到 4Vpp, 静态功耗小于 3mW. 在 1kHz 的正弦波激励下, 其 THD 小于 0.003%. 还提出了一种新型的过流保护电路, 可以对片内大功率输出级电路进行有效的保护.

关键词: 系统矫正结构; CMOS 功率放大器; 过流保护电路

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