A Low Noise, Low Residual Offset, Chopped Amplifier for Mixed Level Applications

M.A.T. Sanduleanu[1], A.J.M. van Tuijl[2], R.F. Wassenaar[1], M.C. Lammers[1] and H.Wallinga[1]
[1]University of Twente, Department of Electrical Engineering
P.O.Box 217, 7500 AE Enschede, The Netherlands
E_mail: m.a.t.sanduleanu@el.utwente.nl
[2]Philips Semiconductors, Nijmegen, The Netherlands

Abstract: **This paper describes the principle and the design of a CMOS low noise, low residual offset, chopped amplifier with a class AB output stage for noise and offset reduction in mixed analog digital applications. The operation is based on chopping and dynamic element matching to reduce noise and offset, without excessive increase of the charge injection residual offset. The main goal is to achieve low residual offsets by chopping at high frequencies reducing at the same time the 1/f noise of the amplifier. Measurements on a 0.8μm CMOS realization show reduction of 1/f noise and 18nV/√Hz residual thermal noise at low frequencies. The residual offset is lower than 100μV up to 8MHz chopping frequency. Driving a 32Ω load the linearity is better than -80dB and better than -88dB for a 1kΩ load at 1KHz.**

1. INTRODUCTION

Analog signal processing functions in a digital environment have to face the reduction in the power supply voltage and the increase of 1/f noise due to the tuning of the process towards digital performance. In order to keep the same dynamic range, the solution would be to keep the largest possible swing and to reduce the 1/f noise by chopping. In conventional chopper stabilized opamps [1], [2], [3] for 1/f noise and offset reduction, differential amplifiers are used (see fig.4) and the bandwidth is limited to few tens of KHz. Switching at the differential output will introduce most of the switching noise and residual offset. Other solutions for offset reduction like ping-pong techniques [4] have the disadvantage of high power consumption and linearity problems. Chopping as a technique for reducing 1/f noise has been considered only for low frequency signals. In order to process signals up to few MHz, one has to be able to increase the chopping frequency without increasing the offset generated by switching feedthrough. Recently, in [5], a chopped transconductance amplifier has been presented. This amplifier is capable of chopping up to 1MHz but the residual offset can be as high as 500μV. However, the large output impedance of the OTA, in a follower configuration, driving the input stage, generates spikes at the output which are responsible for the large residual offsets at frequencies higher than 1MHz. To drive a low ohmic load without an increase in switching offset, a class AB output stage is an obvious choice. In some applications, high linearity is desired and therefore, rail to rail input stages cannot be used. This paper presents a chopped amplifier with a class AB output stage capable of reducing the 1/f noise up to 10MHz without increasing the switching offset. It can drive low ohmic loads (32Ω) with high linearity and low noise.

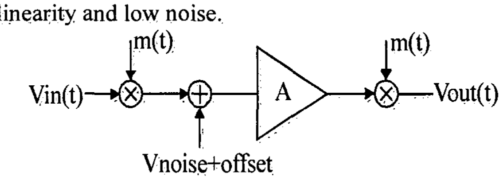

Fig.1: Chopping principle

2. CHOPPING PRINCIPLE

The chopping principle is depicted in fig.1. Here, the input signal is multiplied with a rectangular signal m(t) with unity amplitude and 50% duty-cycle. Offset and 1/f noise are modulated at odd harmonics leaving the baseband free of 1/f noise as shown in fig.2. In the ideal chopping case, the bandwidth of the amplifier should be infinity. As long as this is true, multiplying the signal twice with m(t) will reconstruct the input signal ideally. If the bandwidth of the amplifier is limited, the result is a high frequency residue centered around the even harmonics of the chopper frequency and the signal in the baseband is attenuated. A necessary condition to cancel out the 1/f noise can be derived from fig.2. This condition would be:

$$fchop \geq BW_{signal} + f_{corner} \qquad (1)$$

The effect of chopping on white and 1/f noise can be quantified by considering the power spectral density

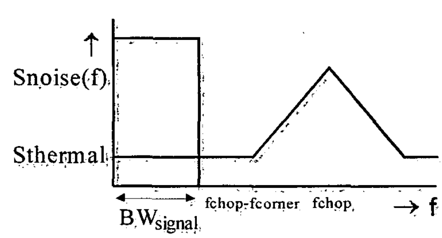

Fig.2: Baseband spectrum at the output

0-7803-5008-1/98/$10.00©1998 IEEE.

of the noise at the output as shown in fig.3. A finite amplifier bandwidth has been assumed. The normalized power spectral density of the white noise remains unchanged, as long as, the bandwidth of the amplifier is about ten times larger than the chopping frequency. Under this condition, the normalized power spectral density of the 1/f noise remains finite at low frequencies. In fig.3 the constant k_F is the 1/f noise constant and depends on the process. As a conclusion, if we want to chop at high frequencies, we need a large amplifier bandwidth compared to chopping frequency in order to reduce 1/f noise and to let the thermal noise unchanged.

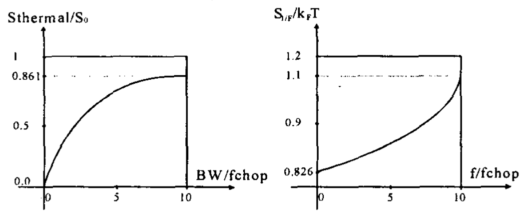

Fig.3: Noise PSD after chopping

3. BASIC PRINCIPLE

In conventional choppers, the signal is transposed at the input of the differential pair, amplified and demodulated at the output nodes as shown in fig.4. Switching at high impedance nodes would be disadvantageous due to limited bandwidth of the amplifier. In this approach, high frequency chopping is not possible and, therefore, this method is limited to few tens of KHz. Besides, the switching noise is directly coupled to the output. Because we have switches in the middle of the supply, for low voltage applications a charge pump is needed. This is to ensure that all switches are firmly open and/or closed. The basic circuit, shown in fig.5, comprises an input modulator, a PMOS differential pair, current sources and a low voltage, high bandwidth, cascoded mirror, to perform a differential to single ended conversion. The second chopper would transpose again the signal at low impedance nodes and demodulates back the signal, canceling out the offset of the bottom transistors. The offset and noise from the current sources would be canceled out by the third chopper which matches dynamically the two transistors on top. There are no consequences on the signal due to the third chopper. The benefit of chopping at low impedance nodes comes from the large bandwidth of the basic amplifier. Therefore, we can chop at much higher frequencies where the only limitation would be the charge injection residual offset. In plus, the cascode transistors provide low-pass filtering for the high frequency spectral contributions coming from chopping. In this approach a charge pump is not needed provided that the common mode voltage is well chosen and switching is close to the supply rails. The output node, used for Miller compensation, filters out the undesired high frequency spectral components from switching, delivering to the class AB output stage an almost offset/noise free voltage. Therefore, an extra low-pass filter is not necessary as would be the case for conventional choppers.

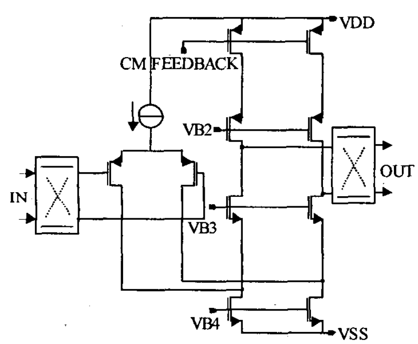

Fig.4: Conventional choppers

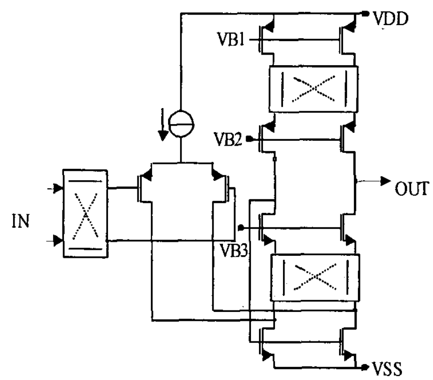

Fig.5: Basic principle

4. CIRCUIT PRINCIPLE

The circuit consists of a chopped transconductance stage and a class AB output stage. In fig.6, the input chopper M30, M31, M32 and M33 transposes the differential input signal applied to the Plus and Min terminals to the alternate output nodes of the modulator. As a result, the signal is modulated at odd harmonics of the chopper frequency. The second chopper M34, M35, M36 and M37 demodulates back the signal and modulates 1/f noise and offset at odd harmonics. In order to cancel out the noise and offset of M8 and M9, the third chopper M38, M39, M40 and M41 matches dynamically the two branches. A cascoded mirror M3, M4, M5 and M6 performs a differential to single ended conversion for the signal which is applied to the output stage. The class AB output stage [6] uses two MOS translinear loops to control the current in the output transistors. The offset of the output stage is mainly caused by mismatch between the currents of M22 and M26. The input stage has 92dB gain. Hence, the 1/f noise and the

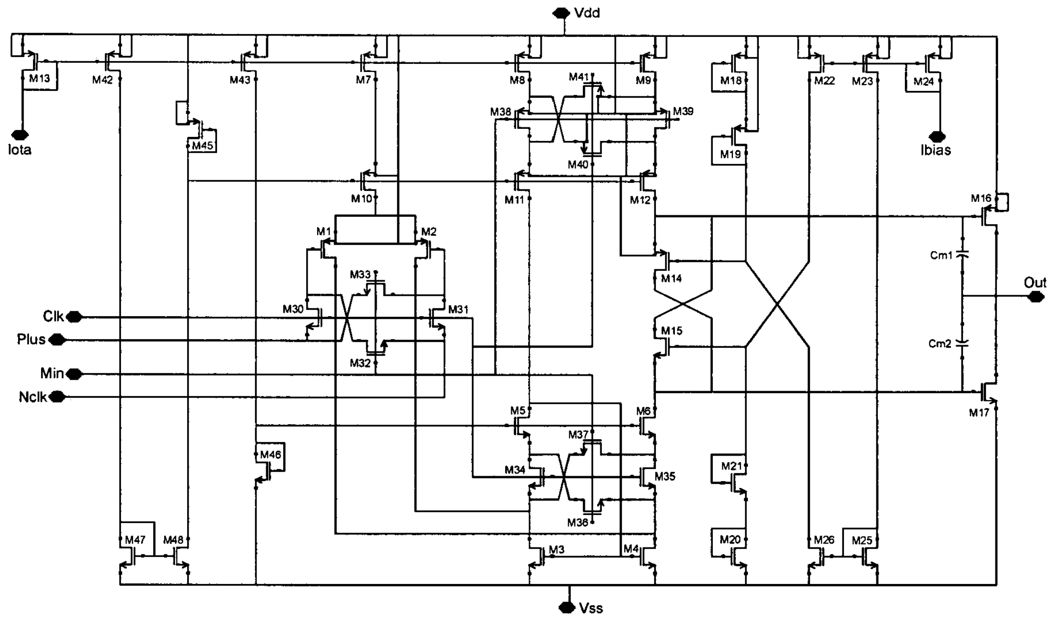

Fig.6: Circuit diagram

offset generated by the output stage can be neglected. The output transistors have large dimensions and can deliver 160mA short circuit current in a rail to rail configuration without latching.

5. MEASUREMENTS

The chopped amplifier has been realized in a 0.8µm CMOS digital technology with one polysilicon layer

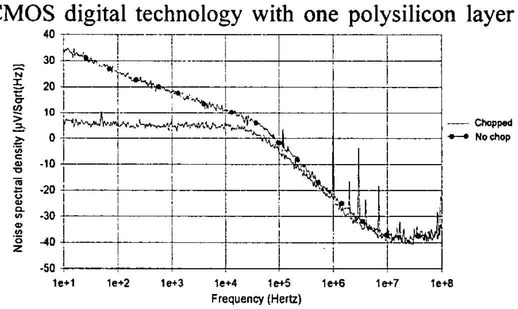

Fig.7: Output noise spectrum

and two metal layers. Ten arbitrarily chosen samples, have been measured. Special layout techniques have been used to reduce the mismatch and charge injection of the switches. The area of the chip is about 0.16mm^2 and a chip photomicrograph is shown in fig.11. In order to consider the effect of chopping on 1/f noise, fig.7 shows the noise spectrum of the opamp. The chopper frequency is 1MHz. At the input, the residual noise is the white noise of the amplifier, attenuated with about 3dB compared to the unchopped case. The rise and fall times of the chopper modulator have an important effect on the reduction of 1/f noise. The larger the transition times, the more important becomes the 1/f noise from the switches which have small dimensions and inherently large noise. Chopping reduces the offset dramatically.

In theory, only the offset of the output stage should remain but, in practice, mismatches of the switches and non-ideal behavior of the chopper signal are the cause of the residual offset when the chopper frequency increases.

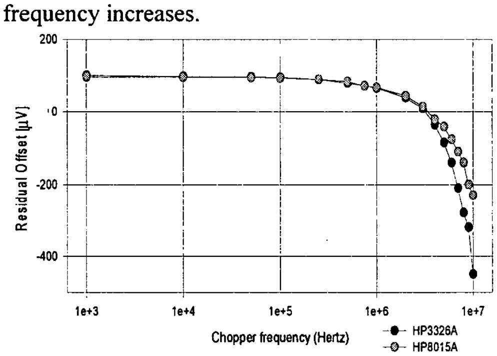

Fig.8: Residual offset

Measured in a follower configuration, the residual offset as a function of the chopping frequency is presented in fig.8. The two graphs correspond to different transition times generated from two different pulse generators. The larger the transition time, the higher the offset. Up to 8MHz, the residual offset is lower than 100µV. This is mainly generated by the output stage. The THD measurement has been done with 1MHz chopper frequency. To be able to use the full swing at the output, the amplifier has been configured as an inverting amplifier with 0dB gain. The linearity measurement, versus amplitude, for two different loads, is considered in fig.9. For high ohmic loads, the THD is better than -91dB for 1.5V voltage swing. For low ohmic loads, the THD is better than -83dB. The THD as a function of frequency is shown in fig.10. The linearity with a 1kΩ load is better than

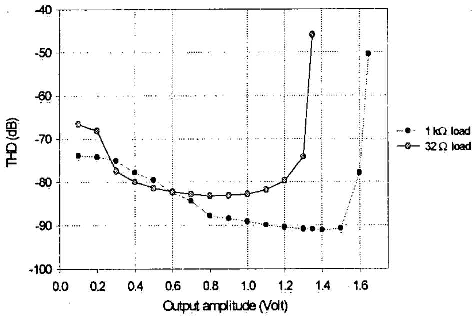

Fig.9: THD vs. output amplitude

the linearity with 32Ω load because the output stage has a higher gain and does not have to deliver large currents. The measured input white noise is 18nV/√Hz which gives a DR of 111dB in audio band. The measurement has been done with 1MHz chopper frequency. A complete summary of performance is given in table 1.

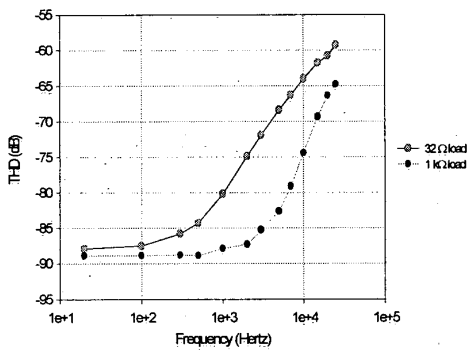

Fig.10: THD vs. frequency

6. CONCLUSIONS

A low-noise, chopped amplifier with a class AB output stage has been presented. It's principle is based on chopping and dynamic element matching to reduce noise and offset without excessive increase of the charge injection residual offset. The main goal of the circuit it is to achieve low noise and low residual offsets by chopping at high frequencies. It can drive low ohmic loads without stability problems with high gain and high linearity, meeting specifications for high end audio applications. The circuit has been realized in a 0.8μm CMOS process. The power consumption is 1.8mW from a 3.3V power supply. It can work down to 1.8V with reduced swing and DR.

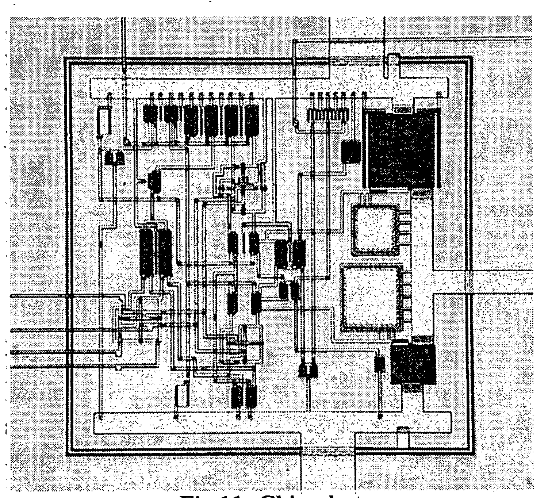

Fig.11: Chip photo

PARAMETER	VALUE
Open-loop gain (A_{OL})	**>74dB (R_L=32Ω)**
GBW	**>3.2MHz**
Phase margin	**81°**
Slew rate	**5V/μs**
Output swing (pp)	**1.9V_{rms}(R_L=32Ω)**
Input white noise	**18nV/√Hz (f_{chop}=1MHz)**
DR(in audio band)	**111dB**
σ(Offset)$_{\mid fchop=0}$	**2.5mV**
Offset$_{\mid fchop<7MHz}$	**<100μV**
THD$_{\mid RL=1k\Omega}$	**-89dB (f=1KHz)**
Power Consumption	**1.8mW**
Supply voltage	**3.3V (minimum 1.8V)**
Area	**0.16mm^2**
Technology	**0.8μm, 1PS, 2AL, CMOS**

Table1: Summary of performance

REFERENCES

[1] A. Bakker and J.H. Huijsing, "A CMOS chopper opamp with integrated low-pass filter", *Proc. ESSCIRC'97*, Southampton, UK, Sept.1997, pp. 200-203.

[2] K.C. Hsieh, P.R.Gray, D.Senderowicz, D.G. Messerschmitt, "A low-noise chopper stabilized differential switched capacitor filtering technique", *IEEE J.Solid-State Circuits.* vol. SC-16, no.6, Dec.1981, pp.708-714.

[3] C. Menolfi and Q. Huang, "A low-noise CMOS instrumentation amplifier for thermoelectric infrared detectors" *IEEE J.Solid-State Circuits.* vol. 32, no.7, July 1997, pp.968-976.

[4] I.E. Opris and G.T.A. Kovacs, "A rail to rail ping-pong opamp", *IEEE J.Solid-State Circuits.* vol. 31, no.9, Sept. 1996, pp.1320-1324.

[5] M.A.T. Sanduleanu, B. Nauta and H. Wallinga, "Low-power, low-voltage chopped amplifier for noise and offset reduction", *Proc. ESSCIRC' 97,* Southampton, UK, Sept.1997, pp.204-207.

[6] D.M. Monticelli, "A quad CMOS single-supply opamp with rail-to-rail output swing", *IEEE J. Solid-State Circuits,* vol.SC-21, no.6, pp.1026-1034, Dec.1986.