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A 440µW, 109.8dB DR, 106.5dB SNDR Discrete-Time Zoom ADC with a 20kHz BW

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Abstract

This paper presents a discrete-time (DT) zoom ADC for audio applications. A 2b quantizer in combination with a low power "fuzz" suppression technique, results in a significant improvement in linearity and energy-efficiency over previous designs. The ADC occupies 0.27mm^2 in 0.16µm CMOS and consumes 440µW from a 1.8V supply. In a 20kHz BW, it achieves 109.8dB DR and 106.5dB SNDR, resulting in a state-of-the-art Schreier FoM of 186.4dB.

Introduction

Zoom ADCs use a coarse low power SAR ADC to dynamically update the references of a Delta-Sigma Modulator (ΔΣM), resulting in both high dynamic range (DR) and energy-efficiency [1,3]. These characteristics make them well suited for use in audio applications. To accommodate SAR non-idealities, previous designs employed 1b ΔΣMs and over-ranging, resulting in a significant loss of SQNR. They also suffered from extra in-band distortion or "fuzz" due to the leakage of SAR quantization noise (Q_{SAR}) [3]. In this work, the DR loss due to over-ranging is mitigated by the use of a 2b ΔΣM, which also enables a significant reduction in over-sampling ratio (OSR), and thus in digital power. Furthermore, a low power fuzz suppression technique is proposed, which significantly suppresses in-band distortion.

Proposed Zoom ADC Architecture

Fig. 1 shows the proposed DT zoom ADC. It consists of a 5b asynchronous SAR ADC and a 3rd order feedforward ΔΣM. The SAR ADC has a quantization step of $V_{LSB\text{-}C}$ and outputs a digital code (k), which satisfies $k \cdot V_{LSB\text{-}C} < V_{IN} < (k+1) \cdot V_{LSB\text{-}C}$. This is used to set the references of the ΔΣM, such that $V_{REF+} = (k+1+M) \cdot V_{LSB\text{-}C}$ and $V_{REF-} = (k-M) \cdot V_{LSB\text{-}C}$, where the over-ranging step M = 1 confers robustness to SAR errors and to mismatch between the SAR and ΔΣM quantization levels.

The DAC of a 1b ΔΣM would then span $3 \cdot V_{LSB\text{-}C}$, wasting SQNR (Fig. 2a) [1,3]. In contrast, the output of a 2b ΔΣM $Y_{\Delta\Sigma}$ uses all the SAR levels, i.e. $(k+\{-1,0,1,2\}) \cdot V_{LSB\text{-}C}$ (Fig. 2b). This increases SQNR by 9 dB and enables lower OSR.

At low OSR, however, Q_{SAR} leakage will cause significant in-band distortion. From [3], the zoom ADC's output can be expressed as $D_{out} = k + Y_{\Delta\Sigma} = V_{IN} + Q_{\Delta\Sigma} \cdot NTF + Q_{SAR} \cdot (STF\text{-}1)$. At high frequencies, the STF of a feedforward modulator will deviate from unity, resulting in Q_{SAR} leakage. Although this can be corrected in the digital domain, the required reconstruction filter is quite complex [3]. In this work, a unity STF is achieved by using a feedforward path to inject a replica of Q_{SAR} into the loop filter just before the quantizer (Fig. 1).

Fig. 3 shows a simplified schematic of the zoom ADC. At the onset of Φ_1, the SAR ADC samples V_{IN} and converts it into a 5b output (k) with negligible delay. During Φ_1, OTA_1 is disconnected from the loop filter, configured in unity gain and then chopped, which mitigates its offset and 1/f noise. Since there is now no signal content at its input, this approach eliminates chopping artefacts. At the end of Φ_1, the ΔΣM samples V_{IN} onto the sampling capacitors $C_{S1\text{-}P}$ and $C_{S1\text{-}M}$ in a fully differential manner, thereby rejecting any CM input. $C_{S1\text{-}P}$ and $C_{S1\text{-}M}$, each consisting of 31 unit elements sized for thermal noise (13.6pF in total), also serve as the feedback CDACs. Their ~13b inherent linearity is significantly improved by using DWA. During Φ_2, the unit elements of the DAC are driven by a 31b unary signal, which is pre-calculated during Φ_1 by combining k and $Y_{\Delta\Sigma}$. The result is then integrated on C_{INT1} (9.1pF). The capacitors of the 2nd and 3rd stage are sized for mismatch, as their noise contribution is negligible. To maximize the modulator's SQNR, C_{notch} creates an NTF notch by establishing a resonant feedback path around the 1st and 2nd integrators. The use of zooming and a 2b quantizer means that the internal loop filter swings are quite small, and so all three stages are built around energy-efficient, high PSRR, current-starved OTAs [3].

The 2b flash-based quantizer consists of a resistive reference ladder (R_u = 72kΩ) and three comparators (Fig. 4). The top and bottom comparators employ continuous-time pre-amps to minimize kickback to the reference ladder, while the mid-level comparator uses a dynamic pre-amp to minimize power consumption, since its kickback will be absorbed by OTA_3 and is mainly CM in nature. To increase the output swing of the loop filter and thus relax the requirements on comparator offset, the threshold voltages are set such that the quantizer gain K_Q is small (~ 1/4). The feedforward path is implemented by replicating Q_{SAR} with a separate input feedforward capacitor C_{inFF} and a 5b CDAC C_{resDAC}, also controlled by k. The capacitor values are sized to implement the optimal feedforward path gain $G = 1/K_Q$ (Fig. 1).

Measurement results

The zoom ADC occupies 0.27mm^2 in a 0.16µm CMOS technology, (Fig. 5). At a sampling frequency f_s of 3.5MHz (OSR = 87.5) it consumes 440µW from a 1.8V supply (46% analog, 19% DAC and 35% digital circuits). Fig. 6 shows the output spectrum with shorted inputs. Chopping at $f_{chop} = f_S/2$ reduces the $1/f$ corner to < 10Hz without impacting the noise floor. Fig. 7 shows the ADC's output spectrum for a -0.5dBFS input at 1kHz. Turning the fuzz suppression scheme "ON" results in a 7.4dB and 2.9dB improvement in THD and peak SNDR, respectively, which is mainly limited by the mismatch between the SAR and feedforward CDACs and by the ΔΣM's residual non-linearity. The measured peak SNR, SNDR, and DR of the zoom ADC are 107.5dB, 106.5dB, and 109.8dB, respectively (Fig. 8). Over the audio band, the measured CMRR is greater than 89dB for a full-swing CM input (Fig. 9). The measured PSRR is 99.2dB at 50Hz, and it remains above 97dB over the audio band (Fig. 9). Fig. 10 shows the total in-band integrated noise in the presence of large (-1.5dBFS) input signals. The ADC is robust to signals up to 80kHz, which is some 3x better than a previous zoom ADC [1]. Table I summarizes the ADC's performance and compares it to the state-of-the-art. This work achieves a $FoM_{S,DR}$ of 186.4dB and FoM_{SNDR} of 183.1dB, which represent the highest energy-efficiency published to date for audio ADCs.

References

[1] B. Gönen, *et al.*, *JSSC*, 2019 [2] C. Lee, *et al.*, *JSSC*, 2019
[3] S. Karmakar, *et al.*, *JSSC*, 2018 [4] S. Billa, *et al.*, *JSSC*, 2017

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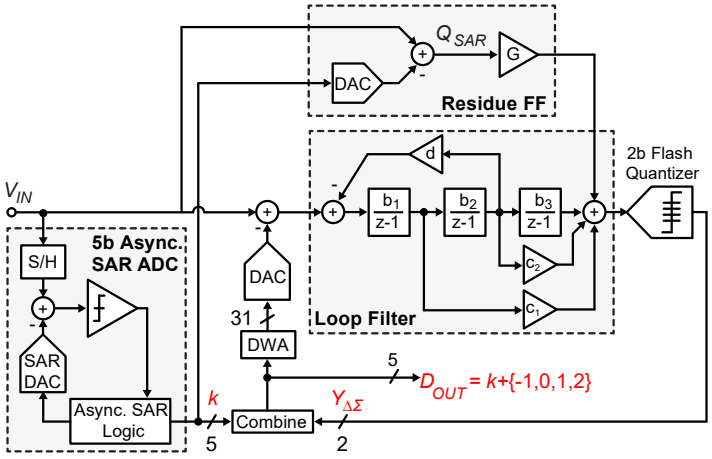

Fig. 1: Proposed DT zoom ADC

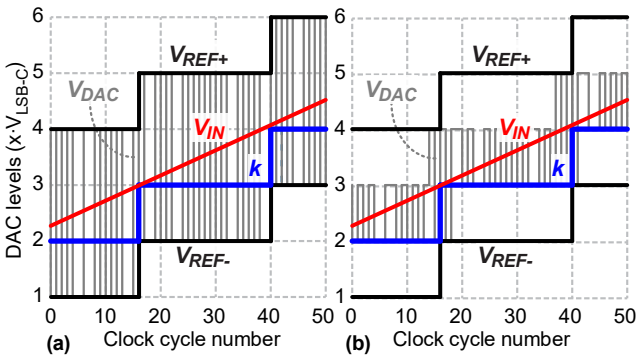

Fig. 2: SAR output (k) and ΔΣM DAC swings with M = 1 for (a) a 1b quantizer and (b) a 2b quantizer

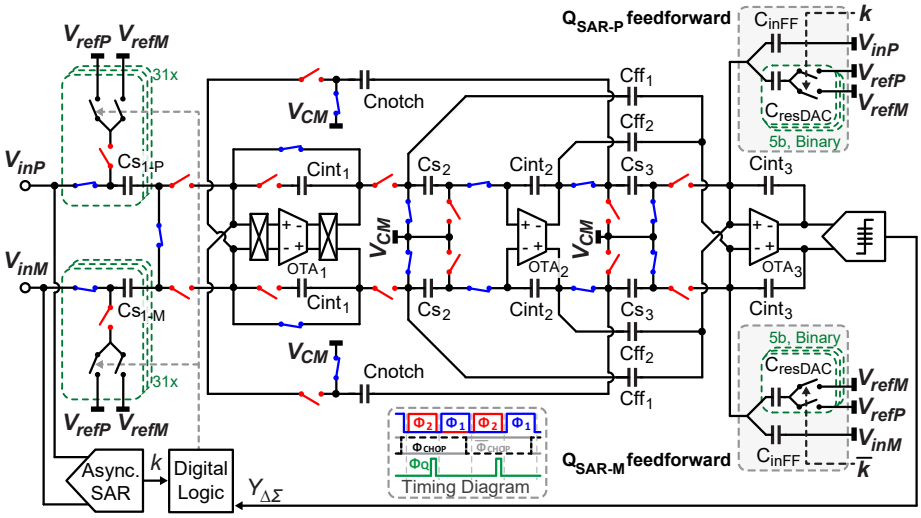

Fig. 3: Schematic of the proposed zoom ADC

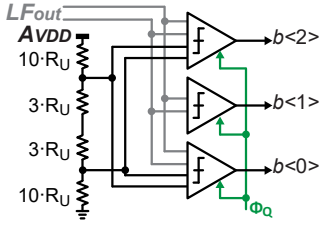

Fig. 4: 2b Flash quantizer

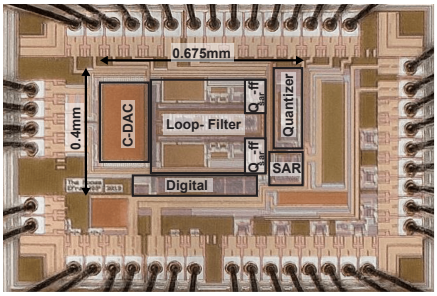

Fig. 5: Die micrograph

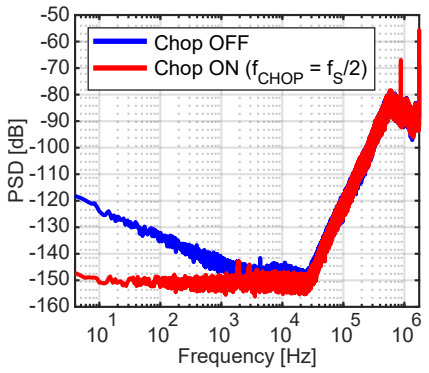

Fig. 6: Meas. PSD w/ and w/o chopping

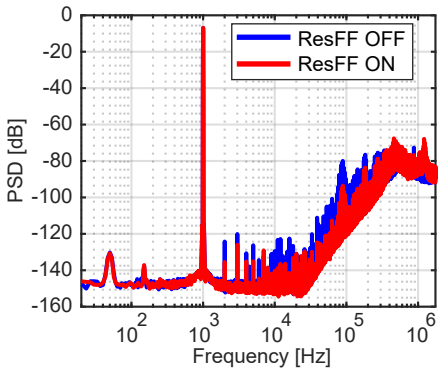

Fig. 7: Meas. PSD w/ and w/o Q_{SAR} ResFF

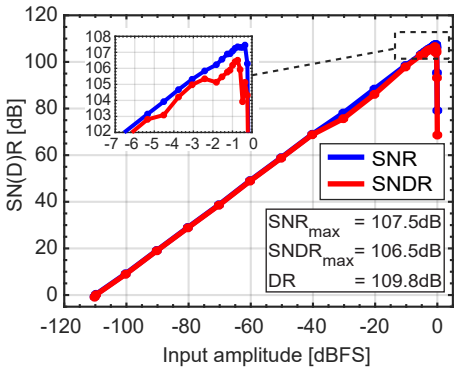

Fig. 8: Meas. SN(D)R across i/p amplitude

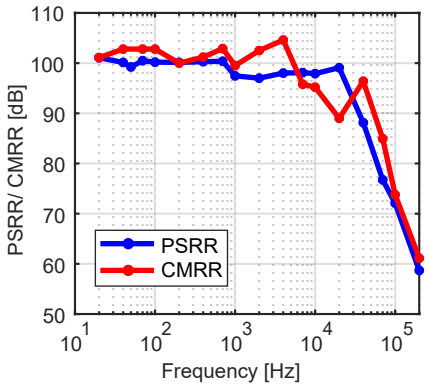

Fig. 9: Measured CMRR and PSRR across input/ supply frequency

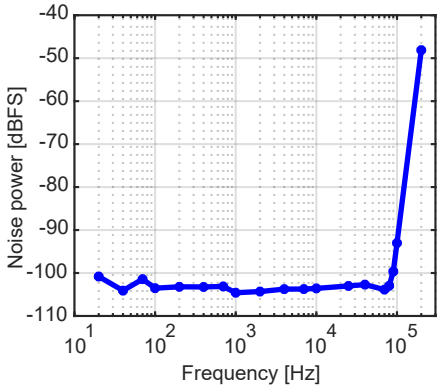

Fig. 10: Total in-band noise power across f_{IN} for a -1.5 dBFS input amplitude

Table 1. Performance summary and comparison

	This work	[1]	[2]	[3]	[4]
Tech (nm)	**160**	160	65	160	180
Area (mm²)	**0.27**	0.27	0.14	0.25	1
Supply (V)	**1.8**	1.8	1.2	1.8	1.8
Power (μW)	**440**	618	68	280	280
f_S (MHz)	**3.5**	5.12	6.144	2	6.144
BW (kHz)	**20**	20	24	1	24
SNR_{max} (dB)	**107.5**	108.1	94.8	119.1	99.3
$SNDR_{max}$ (dB)	**106.5**	106.4	94.1	118.1	98.5
DR (dB)	**109.8**	108.5	98.2	120.3	103.6
FoM^{*}_{SNDR} (dB)	**183.1**	181.5	179.5	183.6	177.8
FoM^{**}_{S} (dB)	**186.4**	183.6	183.6	185.8	182.9

* FOM_{SNDR} = SNDR + $10\log_{10}$(BW/Power) ** FOM_S = DR + $10\log_{10}$(BW/Power)