

Re-configurable Switched Capacitor Sigma-Delta Modulator for MEMS Microphones in Mobiles

M. Grassi, F. Conso, G. Rocca, P. Malcovati and A. Baschirotto

Abstract This paper presents a reconfigurable discrete-time audio Sigma-Delta modulator implemented in 0.18- μm CMOS technology. The $600\text{ }\mu\text{m} \times 400\text{ }\mu\text{m}$ core area SD modulator is based on a $2 + 2$ MASH architecture, and features several different operating modes in which noise-shaping order, number of output word bits, sampling rate, and bandwidth can be programmed ad hoc. By design, the power consumption is minimized for the selected operating mode. The achieved performance ranges from 99-dB DR with 4th-order noise shaping and full standard audio bandwidth, while consuming 0.97 mW down to 85-dB DR with second order noise shaping over reduced bandwidth for vocal control operation, while consuming 100 μW . The developed device can be used either to read-out different sources (microphones) or to operate in different modes within the same system (i.e. with the same microphone in different scenarios). The trade-off between performance and re-configurability is the key element of this work.

Keywords MASH · Sigma-Delta · Data converter · Microphones
Re-configurable · MEMS

1 Introduction

Audio modules are key elements in most portable devices such as mobile phones, tablets or music players and recorders. For instance, in the latest generation of mobiles, simple processing of the audio signal for calls is not enough anymore:

M. Grassi (✉) · P. Malcovati
Dept. of Electrical, Computer, and Biomedical Engineering,
University of Pavia, Pavia, Italy
e-mail: marco.grassi@unipv.it

F. Conso · G. Rocca
Epcos-Europe-TDK, Copenhagen, Denmark

A. Baschirotto
Dept. of Physics, University of Milano-Bicocca, Milan, Italy

© Springer International Publishing AG 2018

A. Leone et al. (eds.), *Sensors and Microsystems*, Lecture Notes in Electrical Engineering 457, https://doi.org/10.1007/978-3-319-66802-4_2

more demanding features such as high-fidelity audio recording, voice commands execution or dictation of text must be available on the device. These new functionalities lead to an enhanced scenario which must deal with an intrinsic trade-off between performance and power consumption. For example, in devices that support voice commands, the audio module must always be active with an extremely low power consumption and a dynamic range (DR) that can be relatively small [1–4]. However, when an input signal is detected, the DR and, therefore, the power consumption can be increased in order to perform the required functions. For example, when the audio acquisition module must be always active to detect voice commands, the bandwidth and DR specifications are of the order of 4 kHz and 70 dB, respectively, accompanied by an extremely limited power consumption (around 100 μ W). On the other hand, in Hi-Fidelity applications the required bandwidth is the standard one (20 kHz) and the DR must be larger than 90 dB, accepting a power consumption of the order of mW. [5–7]. This paper reports a reconfigurable Sigma-Delta (SD) modulator, whose performance can be adapted in real time to the function to be performed. In particular, the noise-shaping order can be programmed (second or fourth order), as well as the bandwidth of the signal (4 or 20 kHz), the sampling frequency (780 kHz, 2.4 MHz, or 3.6 MHz), the bias current (50, 75, or 100% of the nominal value) and the number of bits of the digital output word (single-bit, 2-bit).

2 Reconfigurable Sigma-Delta Modulator

The proposed SD modulator [8] is based on a multi-stage noise shaping architecture (MASH), whose block diagram is illustrated in Fig. 1, and consists of two cascaded second-order stages followed by a digital recombination. The DR and the power consumption obtained in the configurations are summarized in Table 1. It is possible to identify three main modes, defined as “low power” (LP), “standard” (ST) and “high resolution” (HR). When second order noise shaping is selected, only the second stage of the MASH structure is active, while the first stage is turned off. The two switched-capacitor SD modulators of the MASH structure are topologically identical, but in the second stage the values of the capacitors and of the bias currents are reduced. The modulator has been fabricated in 0.18- μ m technology supporting a variable voltage supply from 1.6 to 3.6 V, typical of battery operated systems thanks to a suitable on-chip linear low dropout voltage regulator.

3 Measurements Results

The chip prototype, whose photo is shown in Fig. 2, features a core area of 0.24 mm², including voltage references buffers, which consume 0.29 mW in HR, 0.21 mW in ST, and 30 μ W in LP, and the voltage supply regulator (LDO), which

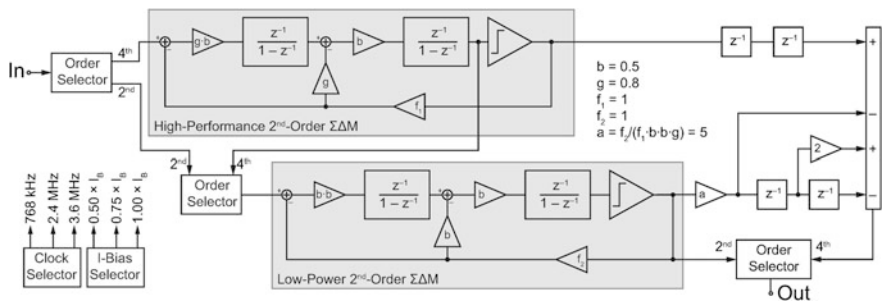


Fig. 1 SD modulator block diagram

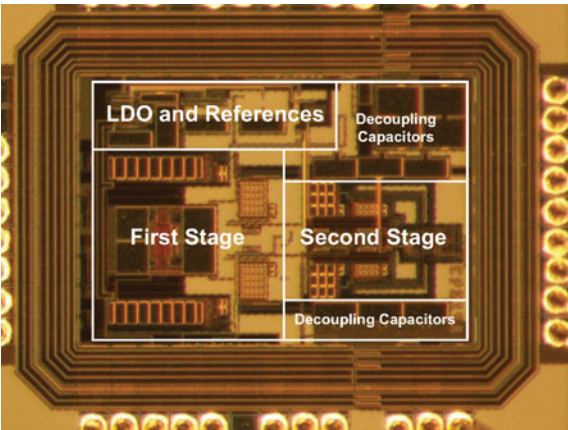
Table 1 SD modulator operating configurations and performance

f_s [MHz]	B [kHz]	2nd-Order		4th-Order	
		Single-bit DR [dB]	Output P [mW]	Multi-bit DR [dB]	Output P [mW]
0.768	4	85(LP)	0.10	99	0.48
	20	59		97	
2.4	4	95	0.15	98	0.73
	20	77		96(ST)	
3.6	4	96	0.20	102	0.97
	20	85		99(HR)	

consumes 40 μ W in HR, ST and 20 μ W in LP. The reference voltages $V_{ref,+}$ and $V_{ref,-}$ are set to 500 mV around the common-mode voltage $V_{cm} = 900$ mV (the full-scale voltage of the SD modulator is thus $2 V_{pp}$).

The spectra of the SD modulator output signal in HR and LP, obtained with an input signal to 1-kHz are shown in Figs. 3 and 4 respectively.

Fig. 2 Chip microphotograph (core + padding)



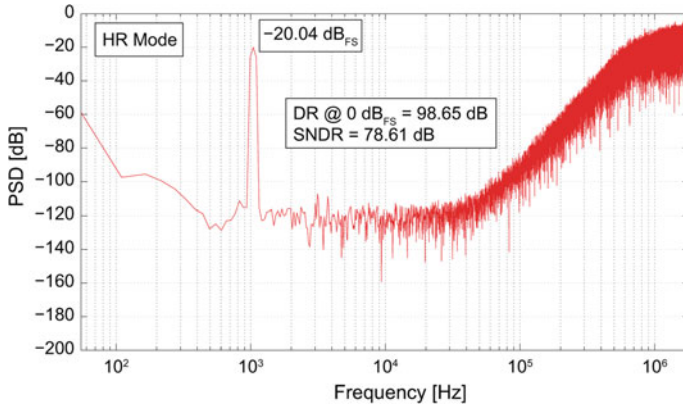


Fig. 3 SD digital output spectrum (HR)

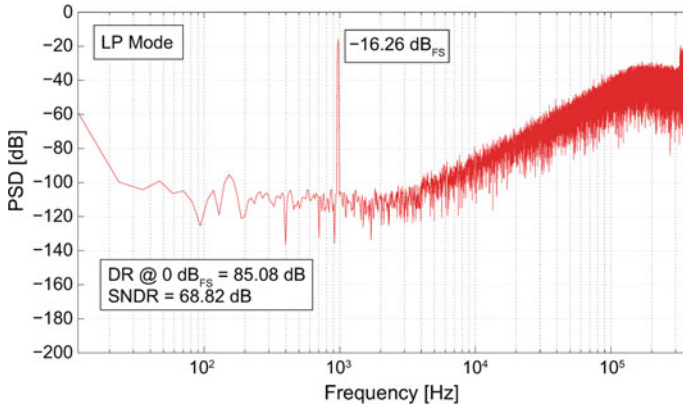


Fig. 4 SD digital output spectrum (LP)

The circuit exhibits a noise shaping of the fourth order in the HR measurement and of the second order in the LP measurement, as expected. The noise floor in HR is about 12 dB lower than in LP due to the reduction of sampling and DAC capacitor values and bias current. Figure 5 shows the signal-to-noise and distortion ratio (SNDR) of the SD modulator as a function of the amplitude of a 1 kHz input signal in HR, ST, and LP configuration.

The circuit achieves a DR of 99 dB in HR, of 96 dB in ST, and of 85 dB in LP configuration respectively. The peak SNDR for large signals is limited in all configurations to about 80 dB due to the harmonic distortion of the source available for the measurements (in the application, considered, the SNDR for audio signals with amplitude larger than 100 dB SPL would be limited in any case to about 75 dB by the harmonic distortion of the MEMS microphone). The optimal SNDR characterization of a SC input SD could be carried out thanks to the availability of an ad

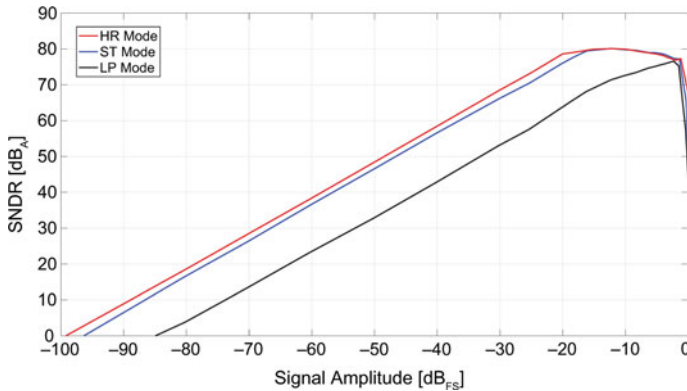


Fig. 5 SD SNDR versus signal amplitude

hoc on-chip pre-amplifier with noise and distortion contributions negligible with respect to the modulator features. Table 1 also summarizes the performances of SD modulator in the three main configurations.

References

1. Badami, K.M.H., et al.: A 90-nm CMOS, 6-mW power-proportional acoustic sensing frontend for voice activity detection. *IEEE J. Solid-State Circ.* **51**(1), 291–302 (Jan. 2016)
2. Park, H., et al.: A 0.7-V 870-mW digital-audio CMOS sigma-delta modulator. *IEEE J. Solid-State Circ.* **44**(4), 1078–1088 (Apr. 2009)
3. Yang, Z., et al.: A 0.5-V 35-mW 85-dB DR double-sampled DS modulator for audio applications. *IEEE J. Solid-State Circ.* **47**(3), 722–735 (Mar. 2012)
4. Christen, T.: A 15-bit 140-mW scalable-bandwidth inverter-based DS modulator for a MEMS microphone with digital output. *IEEE J. Solid-State Circ.* **48**(7), 1605–1614 (July 2013)
5. Yang, Y.Q., et al.: A 114-dB 68-mW chopper-stabilized stereo multibit audio ADC in 5.62 mm². *IEEE J. Solid-State Circ.* **38**(12), 2061–2068 (Dec. 2003)
6. Luo, H., et al.: A 0.8-V 230-mW 98-dB DR inverter-based SD modulator for audio applications. *IEEE J. Solid-State Circ.* **48**(10), 2430–2441 (Oct. 2013)
7. De Berti, C., et al.: A 106.7-dB DR, 390-mW CT 3rd-order SD modulator for MEMS microphones. In: *Proc. ESSCIRC*, 209–212 (Sep. 2015)
8. Grassi, M., Conso, F., Rocca, G., Malcovati, P., Baschiroto, A.: A multi-mode SC audio Sigma-Delta Modulator for MEMS microphones with reconfigurable power consumption, noise-shaping order, and DR. In: *42nd European Solid State Conference Proceedings - ESSCIRC 2016, Lausanne, 12–15 September 2016*, pp. 245–248, IEEE (2016)

Sensors and Microsystems

Proceedings of the 19th AISEM 2017 National
Conference

Leone, A.; Forleo, A.; Francioso, L.; Capone, S.;
Siciliano, P.; Di Natale, C. (Eds.)

2018, XI, 330 p. 146 illus., Hardcover

ISBN: 978-3-319-66801-7