Low-Noise Multirate SC Read-Out Circuitry for Thermoelectric Integrated Infrared Sensors

Piero Malcovati, Carlos Azaredo Leme, R. Lenggenhager, Franco Maloberti, Senior Member, IEEE, and Henry Baltes

Abstract—In this paper we present a switched-capacitor multirate read-out circuit for integrated thermoelectric infrared sensors. The target application is a passive intrusion detector. The signal generated by the sensor in this particular case is quite small (few tens of μV) and has a narrow bandwidth (0.1-10 Hz). It must be amplified (keeping the noise level as low as possible) and filtered. The proposed solution consists of an auto-zeroed low-noise transconductance stage followed by a multirate switched-capacitor integrator. The transconductor transforms the sensor output voltage in a current which is then processed by the integrator. The proposed circuit and the infrared sensor were integrated in a 1.2 μm industrial CMOS technology. Simulations and experimental measurements on the integrated prototype demonstrate the validity of the proposed approach.

I. INTRODUCTION

INFRARED SENSORS are important elements in a number of electronic applications. One of them, with a relevant industrial impact, is the passive intrusion detection. These systems collect the thermal radiation emitted by an intruder and generate an alarm signal. Therefore, the infrared signal in the environment must be detected and processed in order to distinguish an intruder from other thermal signals coming from the surroundings. Intelligent algorithms and signal-processing circuits are needed to perform this task.

Intrusion detectors consist of a mirror system, an infrared detector and intelligent signal-processing electronics. The mirror divides the room to be supervised into different segments (Fig. 1), reflecting and focusing the infrared radiation generated by the intruder on the sensing element. To avoid false alarms due to sunlight or standing heaters, the differential signal between two equal sensing elements is detected. The image of a dislocating intruder shifts from one sensor to the other, leading to an alarm signal. Pyroelectric sensors [1] are commonly used for this application. Unfortunately they are not compatible with the standard IC technologies.

By contrast, thermoelectric infrared sensors can be co-integrated with the analog interface on the same chip. Therefore, even if they are less sensitive than pyroelectric sensors, the on-chip read-out circuitry can compensate this limitation, allowing competitive performance. Moreover, the advantages of an integrated intelligent solution are available. We can

reduce the size and increase the reliability of the complete system. Additional on-chip processing functions can furthermore improve the performance of the sensor and, finally, the cost of the system is minimized.

In this paper we present a CMOS low-noise multirate switched-capacitor read-out circuit designed for co-integration with a thermoelectric infrared sensor on the same chip. The target application is a passive intrusion detector. The circuit has to amplify the very low-level sensor signal to a safe value, to perform a low-pass filtering and to reject the DC component.

II. THERMOELECTRIC INFRARED SENSOR

Thermoelectric infrared sensors are based on the Seebeck effect [2]. A thermocouple, consisting of two junctions of two different conductors at different temperatures, generates a voltage proportional to the temperature difference. In order to increase the output voltage, a number of thermocouples are connected in series, to form a thermopile [3].

A thermoelectric infrared sensor consists of a thermally isolated absorbing area and a thermopile with the “hot” junctions in the absorbing area and the “cold” junctions on a heat sink. Fig. 2 shows the cross-section of a thermoelectric infrared sensor realized in a standard CMOS technology. The absorbing area is an oxide/nitride membrane, obtained by anisotropic etching of the silicon bulk from the back of the wafer. The thermocouples consist of p-doped and n-doped polysilicon lines embedded into the membrane.

Fig. 1. Passive intrusion detector.

Manuscript received May 10, 1994; revised January 19, 1995.

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IEEE Log Number 9411519.
Sensor prototypes have been integrated and characterized. The obtained responsivity is around 120 V/W. When the sensor is used for passive intrusion detection, this leads to an output signal of tens of μV. The output resistance of the thermopile is 2 MΩ.

III. READ-OUT CIRCUITRY REQUIREMENTS

The requirements for the read-out circuitry are summarized in Table I. The low level (5 μV) and the small bandwidth (0.1–10 Hz) of the signal make the design of the first amplifier of the processing chain in CMOS technology very challenging.

Table I: Electrical Specifications

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power supply</td>
<td>5 V</td>
</tr>
<tr>
<td>Technology</td>
<td>CMOS</td>
</tr>
<tr>
<td>Input range</td>
<td>5 ± 50 μV</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>0.1–10 Hz</td>
</tr>
<tr>
<td>Input resistance</td>
<td>&gt; 100 MΩ</td>
</tr>
<tr>
<td>Total noise in the band 0.1–10 Hz</td>
<td>5 μV</td>
</tr>
</tbody>
</table>

Usually CMOS low-noise amplifiers are realized using compatible lateral bipolar transistors for the input stage, because of their low flicker noise contribution [4]. Unfortunately, since the input impedance of bipolar transistors is inherently low (maximum 1 MΩ), this solution is not suitable for this particular application.

The equivalent circuit of the system, including the noise sources, is shown in Fig. 3. The thermal noise power spectral density of the thermopile is white and given by

$$S_{NT} = 4kTR_f = 6.62 \times 10^{-14} T = 300 K \frac{V^2}{Hz}$$  \hspace{1cm} (1)

where $k$ is the Boltzmann constant and $T$ is the absolute temperature. In order to limit the integrated noise voltage below 5 μV, it is necessary to low pass filter the white noise with an equivalent bandwidth of 20 Hz.

On the other hand, the noise contribution of the read-out circuitry has a white term ($S_{NL.th}$) and a flicker term ($S_{NL.f}$). It is given by

$$S_{NL} = S_{NL.th} + S_{NL.f} = \frac{2kT}{3g_m} + \frac{k_F}{C_{os}Wf}$$  \hspace{1cm} (2)

where $g_m$ is the transconductance of the input stage and $k_F$ is a process-dependent parameter.

The white noise contribution of the sensor represents the upper limit for the input referred noise of the analog read-out circuitry. Since the thermopile output resistance is large, the thermal noise of the analog interface is negligible ($S_{NL.th} < 0.01S_{NT}$, if $g_m > 10 \mu S$), but, in the considered band (0.1–10 Hz), the flicker noise is quite large. In order to fit the specifications we must get rid of it. This can be achieved, for example, using a sampled data auto-zero technique [5].

IV. SYSTEM DESCRIPTION

The switched-capacitor technique is very suitable for this application, because it allows to implement on-chip the flicker noise cancellation and the large time constants required in the low-frequency signal processing [6].

Fig. 4 shows the block diagram of the proposed low-noise SC read-out circuit. It consists of a transconductance followed by a multirate switched-capacitor integrator. In order to minimize the clock feed-through and to optimize the processing function, we used a fully differential structure. Therefore, the two sensors are connected to the positive and negative input of the low-noise amplifier, respectively. This arrangement directly produces a fully differential signal, assuming the same operating conditions and sensitivity.

The capacitor $C_{lp}$, together with the output resistance of the thermopile, realizes the anti-aliasing filter. The input amplifier used is a fully differential transconductance stage with two input differential pairs. The flicker noise cancellation is achieved by the auto-zero technique. During one of the two clock phases ($\Phi_{az}$) the inputs of the main differential stage
are shorted, while the outputs of the amplifier are connected to the inputs of the other differential stage (auxiliary stage), realizing a negative feedback.

The voltage at the output of the amplifier, which is equal to the input referred offset (and flicker noise), is sampled and held on two capacitors \(C_{ax} \). During the successive clock phase \(\Phi_{ax} \), read-out phase), the feedback loop is opened, and the sensor signal is connected to the main input of the amplifier. The voltage stored on \(C_{ax} \), applied to the auxiliary input, cancels the offset and the low-frequency noise components.

Because of the finite gain of the transconductor a residual offset (and flicker noise) is expected after the auto-zero phase. When referred to the main input it is given by

\[
V_{\text{res}} = \frac{V_m}{1 + A_n} + \frac{V_n}{A_m}
\]

(3)

where \(A_m, V_m, A_n \) and \(V_n \) are the voltage gain and the input referred offset (and flicker noise) of the two differential pairs (main and auxiliary), respectively.

During the auto-zero phase the transconductance stage is not loaded and, therefore, the voltage gain \(g_{me}^{\text{out}} \) is large. By contrast, during the read-out phase a multirate switched-capacitor network is connected to the output of the transconductor to integrate the output currents, allowing to perform filtering or DC cancellation.

The low-pass filtering is realized by introducing a damping capacitor in the integrator \((C')\). The cut-off frequency (with a roll-off of 20 dB per decade) is controlled by the clock frequency and the capacitance ratio \((C/C')\).

The cancellation of the DC component of the input signal is obtained by square wave modulation of the transconductor current \((\text{MOD})\). The current signals are integrated for \(N_{\text{MOD}} \) clock periods with one sign and then with the opposite sign for the same number of periods \(f_{\text{out}} \). At the end of this second integration phase the output is sampled \(f_{\text{out}} \), and the integrating capacitors \((C)\) are reset \(f_{\text{2}} \). The gain of the circuit, in the band of interest, is determined by the frequency of the clock \(f_{\text{2}} \), which controls the integration time.

The transconductor and the operational amplifier used are based on the same folded cascode p-channel input differential stage, shown in Fig. 5, while they differ in the biasing and common-mode feedback circuits.

![Fig. 5. Folded cascode differential stage used in the transconductor and in the operational amplifier.](image)

![Fig. 6. Microphotograph of the chip.](image)

![Fig. 7. Measured output voltages (out and nout) and spectrum of the differential signal (out minus nout), obtained applying a 500 \(\mu\)Vpp, 5 Hz sinusoidal voltage at the input.](image)

V. EXPERIMENTAL RESULTS

We integrated a prototype of the read-out circuitry in a conventional 1.2 \(\mu\)m CMOS analog technology. A microphotograph of the chip is shown in Fig. 6. In order to ensure the maximum testing flexibility, the sensors are not directly connected to the read-out circuitry, but some pad openings are available for local bonding.

The two measured output voltages (positive and negative) and the spectrum of the differential signal, obtained by applying a 500 \(\mu\)Vpp sinusoidal voltage at the input, are shown in Fig. 7. The frequency of the input signal is 5 Hz. We can observe that the noise spectrum is white (the flicker noise was successfully canceled) and that the signal-to-noise ratio is large enough to fit the specifications (a 5 \(\mu\)V signal can be easily detected). The residual DC component is mainly due to the clock feed-through. The obtained gain is 60 dB.

In order to test the performance of the system in real operating conditions, we connected the sensor and the read-out circuitry. Fig. 8 shows the output signal (waveform 1) obtained by focusing chopped infrared radiation on the sensor (waveform 2 is the 3 Hz chopping signal). The power density of the radiation is 2 \(\mu\)W/mm\(^2\) (corresponding to a temperature difference of 3 K), and the active area of the sensor is
0.84 mm². The total power collected is therefore 1.68μW. In this case the gain of the amplifier is 75 dB. We can observe that the noise level is well below the signal level.

VI. CONCLUSION

In this paper we presented a low-noise switched-capacitor multirate read-out circuit for integrated thermoelectric infrared sensors, to be used in a passive intrusion detector.

The very low-level and low-frequency signal generated by the sensor (few μV in the band 0.1–10 Hz) must be amplified and band-pass filtered. The flicker noise level, compared with the signal, makes the design of the input stage in CMOS technology very challenging. Nevertheless, using the switched-capacitor technique, it is possible to reduce the flicker noise and to perform, at the same time, the required low-frequency signal processing.

We used a design strategy which allows user flexibility. Therefore, the circuit is also suitable for many other applications. A prototype was integrated in CMOS technology and tested. The results obtained demonstrate the validity of the proposed approach.

REFERENCES


Piero Maloberti, for a photograph and biography, please see this issue, p. 650.

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Henry Baltes, for a photograph and biography, please see this issue, p. 651.