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

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Abstract — In this paper we present a switched capacitor multirate read-out circuit for thermoelectric infrared sensors integrated on chip. The target application is a passive intrusion detector. The signal generated by the sensor in this particular application is quite small (few tens of μV) and has a narrow band-width (0.1 - 10 Hz). It must be amplified (keeping the noise level as low as possible) and band pass filtered. An auto-zeroed low-noise transconductance stage transforms the sensor output voltage in a current, which is applied to a multirate switched capacitor integrator, performing the signal processing. A prototype was integrated in a 1.2 μm CMOS technology. Simulation and experimental results are reported.

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.

Pyroelectric sensors 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 dedicated sensors, the on-chip read-out circuitry can compensate this limitation, allowing to achieve competitive performances.

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 performances 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.

The thermoelectric infrared sensor and the system specifications are described in Section II and Section III respectively. The proposed read-out circuitry is presented in Section IV and, finally, the experimental results are reported in Section V.

II. THERMOELECTRIC INFRARED SENSOR

Thermoelectric infrared sensors are based on the Seebeck effect [1]. 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.

Since the Seebeck effect is self generating, the thermoelectric infrared sensor does not need biasing. Moreover, it can sense DC signals without any chopping system.

The 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 [2].

Fig. 1 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.

Passive intrusion detectors work with infrared radia-
tion wavelengths between 8 and 14 μm. In this range the passivation layer provided by the CMOS process shows absorption bands. Therefore it is not necessary to deposit an additional black layer on the membrane.

![Cross-section of a thermoelectric infrared sensor integrated in a standard CMOS process.](image)

Fig. 1 Cross-section of a thermoelectric infrared sensor integrated in a standard CMOS process.

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.

In this particular application, in order to detect the movement of the intruder and to get rid of the false alarms due to common mode signals (for example the sun light), we use two sensors and we take the difference between their output voltages.

III. READ-OUT CIRCUITRY REQUIREMENTS

The requirements for the read-out circuitry are summarized in Table 1. 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>
<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 [3]. 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. 2.

![Noise equivalent circuit of the sensor and the read-out circuitry.](image)

Fig. 2 Noise equivalent circuit of the sensor and the read-out circuitry.

The thermal noise power spectral density of the thermopile is white and given by:

$$ S_{NT} = 4kTR_T = 6.62 \times 10^{-14} \frac{V^2}{Hz}, \quad (1) $$

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 ($S_{NI,th}$) and a flicker term ($S_{NI,f}$). It is given by:

$$ S_{NI} = S_{NI,th} + S_{NI,f} = \frac{24kT}{3g_m} + k_F, \quad (2) $$

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 ($S_{NI,th} < 0.01 S_{NT}$, 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 [4].

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 [5].

Fig. 3 shows the block diagram of the proposed low noise SC read-out circuit. It consists of a transconductor followed by a multirate switched capacitor integrator.

![Block Diagram of Proposed SC Read-out Circuit](image)

**Fig. 3** Schematic and timing diagram of the proposed SC read-out circuitry.

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 thermopiles, 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. One of the two clock phases ($\Phi_{ax}$) 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 ($C_{az}$). During the successive clock phase ($\Phi_{az}$, 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 $C_{az}$, applied to the auxiliary input, cancels the offset and the low frequency noise components.

Of course, 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:

$$V_{res} = \frac{V_m}{1 + A_m} + \frac{V_a}{A_m}$$

(3)

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

During the auto-zero phase the transconductance stage is not loaded and, therefore, the voltage gain ($g_m r_{out}$) 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 both the filtering and the DC cancellation.

The low pass filtering is realized 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 (MOD). The current signals are integrated for $N_{MOD}$ clock periods with one sign and then with the opposite sign for the same number of periods ($f_{mod}$). At the end of this second integration phase the output is sampled ($f_{out}$) and the integrating capacitors ($C$) are resetted ($f_2$).

The gain of the circuit, in the band of interest, is determined by the frequency of the clock $f_2$, which controls the integration time.

The transconductor and the operational amplifier used are based on the same folded cascode p-channel input differential stage. They differ in the biasing and common mode feedback circuits. The transconductor has also an additional differential pair for the offset and low frequency noise compensation.

V. RESULTS

We integrated a prototype of the read-out circuitry in a conventional 1.2 µm CMOS analog technology. The most important design parameters are summarized in Table 2.

It can be observed that the transconductance of the main input stage ($g_{m,main} = 535 \mu$S) of the OTA completely satisfies the thermal noise requirement (equation 2) and that the voltage gain of the auxiliary input stage (69 dB) ensures a sufficiently small residual flicker noise (equation 3).

A microphotograph of the chip is shown in Fig. 4. 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 experimental measurements on the prototype demonstrate the validity of the proposed approach.
Table 2 - Design parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Transconductor OTA</th>
<th>Operational Amplifier</th>
</tr>
</thead>
<tbody>
<tr>
<td>$g_{m,main}$</td>
<td>535 $\mu$S</td>
<td>791 $\mu$S</td>
</tr>
<tr>
<td>$g_{m,auxiliary}$</td>
<td>256 $\mu$S</td>
<td>—</td>
</tr>
<tr>
<td>$r_{out}$</td>
<td>11.3 $\Omega$</td>
<td>11.3 $\Omega$</td>
</tr>
<tr>
<td>GBW$_{main}$</td>
<td>27 MHz</td>
<td>35 MHz</td>
</tr>
<tr>
<td>GBW$_{auxiliary}$</td>
<td>15 MHz</td>
<td>—</td>
</tr>
<tr>
<td>PM$_{main}$</td>
<td>65°</td>
<td>60°</td>
</tr>
<tr>
<td>PM$_{auxiliary}$</td>
<td>75°</td>
<td>—</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>SC integrator</th>
</tr>
</thead>
<tbody>
<tr>
<td>C/C'</td>
<td>40</td>
</tr>
<tr>
<td>$f_{az}$</td>
<td>10 kHz</td>
</tr>
<tr>
<td>$f_2$</td>
<td>500 Hz</td>
</tr>
</tbody>
</table>

Fig. 5 shows the two output voltages (positive and negative) and the spectrum of the differential signal, obtained applying a 500 $\mu$Vpp sinusoidal voltage at the input. 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. Field tests of the complete system are in progress.

VI. CONCLUSIONS

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 $\mu$V 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 used approach.

REFERENCES