UNIVERSITÀ DEGLI STUDI DI PAVIA

CORSO DI DOTTORATO IN MICROELETTRONICA

"Readout Circuits for Integrated Contact-less Temperature Sensors"

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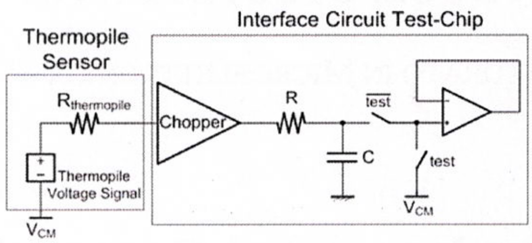
Ph.D. Student: Elisabetta Moisello

Cycle: XXXIII

Research activity:

Exploiting the well known relation between the thermal radiation emitted by an object and its temperature, as expressed by the Stefan-Boltzmann law, thermal sensors allow quick, almost instantaneous, contact-less temperature measurements. Thermal sensors can be employed in a wide range of applications: security systems, fever detection, automotive applications, climate control systems, continous temperature monitoring in manufacturing processes, absorbing measurements for gas analysis, appliances and consumer products. My research activity has been focused on fever detection and motion and presence sensing applications, employing thermal sensors that are fully compatible with standard CMOS processes. The ultimate goal, in fact, is realizing a complete sensor-readout circuit system that could be integrated in a mobile device. For example, if such a system was integrated in a smartphone, it would be possible, exploiting the smartphone's camera, suitably adapted and paired with an appropriate optical system to collect the IR radiation emitted by the body and direct it on the integrated thermal detector, to provide the user with a fever measurement through a software application.
Among the nowadays available thermal sensors, thermopiles are particularly apt for integration in mobile devices, as they distinguish themselves for the advantages of being self-powered and fully compatible with standard CMOS processes, as they can be realized by micromachining using MEMS technology.
In my research activity I considered a miniaturized micromachined p/n polysilicon thermopile realized by STMicroelectronics, and I designed an interface circuit specifically tailored on the sensor characteristics, in order to perform fever measurements, fulfilling the repeatability and ±0.3 °C accuracy requirements. As such specifications are more stringent than the ones required by motion and presence sensing, the proposed sensor-interface circuit system can be employed for those applications as well.
The design of the interface circuit, employing a single-ended chopper amplifier architecture, was the focus of the first year of my Ph.D. In my second year, I performed measurements on the interface circuit test-chip prototype, fabricated in a standard 130-nm CMOS process, characterizing it both as a stand-alone device and as a system together with the thermopile sensor.
A schematic diagram of the interface circuit test-chip prototype and its connection to the thermopile sensor is reported in Fig. 1(a). A passive low-pass filter and an output buffer were also integrated. The filter, whose cutoff frequency is 5 Hz, removes the modulated offset, moved at the chopping frequency and its odd harmonics due to the chopper action, while the buffer drives the output pad. Two CMOS switches were added in order to enable a test mode for the output buffer, during which the offset of the buffer is measured, so it can be taken into account when the signal measurement is performed. In this way, I was able to derive the measurement of the residual offset of the chopper amplifier alone. A die photo of the interface circuit prototype is reported in Fig. 1(b).



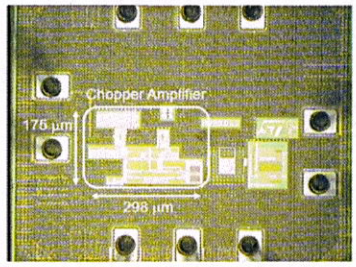


Fig. 1 – (a) Schematic diagram of the interface circuit test-chip and its connection to the thermopile sensor, (b) Microphotograph of the proposed interface circuit.

The interface circuit prototype was fully characterized as a stand-alone device, considering a batch of 29 samples: this allowed obtaining an acceptable statistical characterization.
To verify the correct operation of the chopper structure and measure the residual offset, only the common-mode voltage, and no signal, was applied to the circuit. This measurement was performed at first with the clock signal connected to ground (chopper off) and then supplying a 2-kHz 0-1.2-V square wave with a function generator (chopper on). The obtained standard deviation values at the output are, with the chopper off and with the chopper on, 34.85 mV and 136.5 µV. To derive the input referred standard deviation value, the standard deviation at the output was divided by the amplifier ideal gain, i.e. 100. The resulting offset standard deviation values at the input are, therefore, 348.5 µV with the chopper off and 1.365 µV with the chopper on. Hence, the chopper reduces the offset standard deviation approximately by a factor 255.

COMPARISON WITH STATE-OF-THE-ART AMPLIFIERS SUITABLE FOR THERMOCOUPLE-BASED SENSORS

Parameter	This work	[12]	[13]	[14]
Year published	2019	2012	2016	2017
Technology	0.13-µm CMOS (ST)	0.7-µm CMOS	0.6-µ BiCMOS	0.32-µm CMOS (BCD6s ST)
Area [mm^2]	0.605 (0.0522 amplifier only)	1.8	1.626	0.57
Supply voltage [V]	1.2	5	1.8-to-5.5	3.3
Supply current [µA]	244 (210 amplifier only)	143	1650	170
Power consumption [µW]	292.8 (252 amplifier only)	715	2970 (with 1.8 V)	561
Chopping frequency [kHz]	2	30	150	20
Input offset standard deviation [µV]	1.365 (29 samples)	0.65 (12 samples)	–	2 (5 samples)
Input offset worst case [µV]	2.3 (29 samples)	<2 (12 samples)	3.5	–

[12] Q. Fan, J. H. Huijsing, and K. A. A. Makinwa, "A 21 nV/$\sqrt{Hz}$ chopper-stabilized multi-path current-feedback instrumentation amplifier with 2 μV offset," *IEEE J. Solid-State Circuits*, vol. 47, no. 2, pp. 464–475, Feb. 2012.
[13] V. Ivanov and M. Shaik, "A 10 MHz-bandwidth 4 μS-large-signal-settling 6.5 nV/$\sqrt{Hz}$-noise 2 μV-offset chopper operational amplifier," in *IEEE ISSCC Dig. Tech. Papers*, Jan./Feb. 2016, pp. 88–89.
[14] F. Butti, M. Piotto, and P. Bruschi, "A chopper instrumentation amplifier with input resistance boosting by means of synchronous dynamic element matching," *IEEE Trans. Circuits Syst. I, Reg. Papers*, vol. 64, no. 4, pp. 753–764, Apr. 2017.

Tab. I

Tab. I illustrates the comparison between the proposed interface circuit and other state-of-the-art amplifiers suitable for thermocouple-based sensors. The proposed amplifier features the second best standard deviation, while the offset worst case is comparable with or even better than the other works. Moreover, as the considered number of samples is the largest, it features the best statistical characterization. The power consumption is the lowest, also when considering the buffer: this makes the proposed circuit more suitable to mobile devices applications with respect to the other ones. Furthermore, the chip area is very limited.
After thoroughly characterizing the interface circuit as a stand-alone device, I tested it together with the thermopile sensor as a system, considering both the fever measurement and the motion and presence sensing applications.
To test the system suitability for contact-less fever measurements, a heater, whose temperature could be regulated by varying the applied voltage, was employed as a target object. In all the reported results, unless otherwise stated, the common-mode voltage and the buffer offset were measured and subtracted from the output voltage measurement: the reported values, therefore, show only the signal. Each measurement was performed acquiring 100 samples with the multimeter at 1.25-Hz rate: the samples were stored in the multimeter buffer, which then returned the average value, that is the value considered for each measurement. Furthermore, the measurements were performed at approximately 25-°C ambient temperature.

Repeatability, required for human body temperature detection, was verified by performing several measurements under the same conditions. The results in the case of 3-cm distance between sensor and target object are reported in Fig. 2.

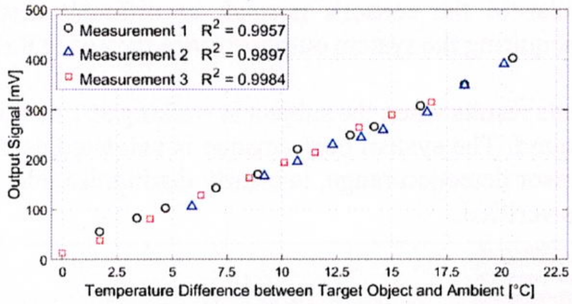


Fig. 2 – Repeated measurements of the thermopile sensor-interface circuit system output with the target object at a 3-cm distance. R^2 is the squared linear correlation coefficient.

Accuracy requirements, however, are not fulfilled, as the measurements suffer from high standard deviation, ranging from 5 to 15 mV, while the sensitivity is 18.40 mV/°C. This measurement degradation is due to environmental noise: in order to reduce it, a perforated metal cap was added to the thermopile sensor. Fig. 3 shows the measurement results with the cap and 3-cm distance between the sensor and the heater as target object. Considering $\pm 2\sigma$, the maximum temperature error is ±0.16 °C, which is perfectly within the accuracy required for human body temperature detection.

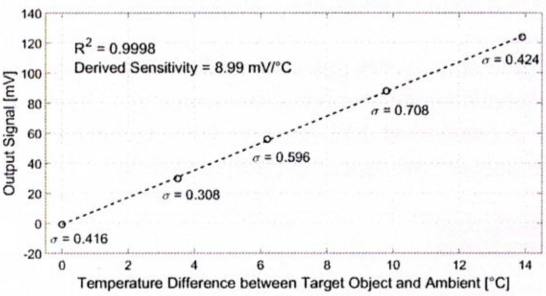


Fig. 3 – Measured thermopile sensor-interface circuit system output with the target object at 3-cm distance, with a cap determining a 51.64° field-of-view (FOV) angle. The standard deviation σ is expressed in mV.

The system suitability for contact-less fever measurements was, therefore, verified.
I also tested the sensor-interface circuit system for presence detection of stationary subjects, considering a person standing in a room at various distances d and angles α from the sensor. The sensor, with the metal cap, and the interface circuit, inserted in their respective boards and connected together, were placed at a 132-cm height from the ground, facing the room. The measurements were performed at 22-°C room temperature, considering a 1.75-m average-build man as the stationary subject. For each identified location, 100 output acquisitions at 1.25 Hz were performed considering both the case with the person standing and the empty room case. The measurement results for each case were stored in the buffer of the multimeter, which then returned the average and standard deviation value. The difference between the average in the occupied room case and in the empty room case was then considered as the output signal of interest.
From the measurements results a fit function was derived to express the signal dependency on distance *d* and angle α:

$$Output\ Signal = c_1\,(\cos\alpha)^{c_2}\,\frac{1}{d^{c_3}}$$

where c_1 =16.17, c_2=4.222 and c_3=1.129, with 95% confidence bounds. The coefficients value were derived employing the Curve Fitting Tool in Matlab.
The fit yields 0.9599-R-squared and 1.52-RMSE (root mean square error): it is therefore a good approximation for the measurements results.

From the measurements results, considering a $\pm 2\sigma$ variation, a positive output signal was found for distances up to 5.5 m. The estimation of the system detection range derived from the fit also verified that the required detection range (a few meters) for the desired application (presence detection in a room) was achieved.
The system performance in the presence of moving subjects was also tested. The subject moved in a straight line, approximately perpendicular to the sensor's normal, at different distances from the sensor. The measurements were performed acquiring the system output voltage through a Keithley 2000 multimeter, paired with a LabVIEW program.
Fig. 4 illustrates the measurements results when the subject is walking at 1 m from the sensor, which is located at a 132-cm height from the ground. The system performance is validated as a peak, corresponding to when the subject moves within the sensor detection range, is clearly distinguishable. Different measurements were performed and repeatability was verified.

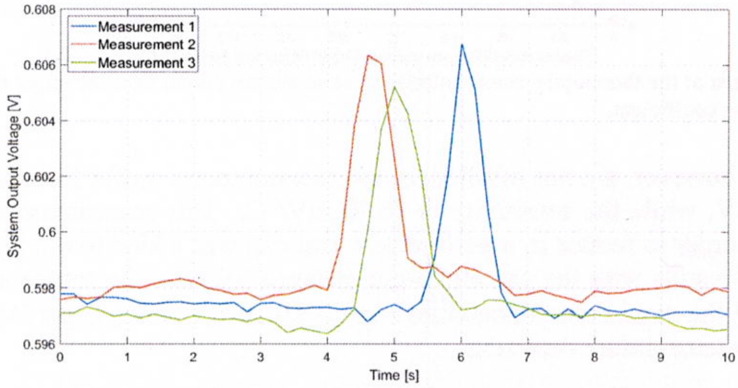


Fig. 4 – Measurements results in the case of a subject walking at 1 m from the sensor, which is located at 132-m from the ground.

Furthermore, the system performance was investigated considering a larger distance, different sensor's heights from the ground and different subject's speed (walking or running). The results in for the subject running at 2.5 m from the sensor, when that is located at 132-cm and 109-cm height from the ground, are illustrated in Fig. 5: the peak, which detects the subject presence, is clearly visible.

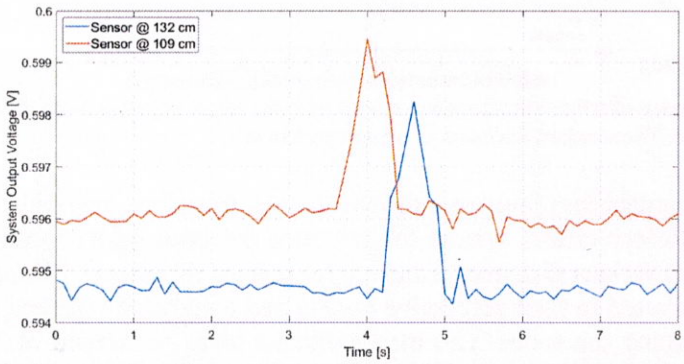


Fig. 6 – Measurements results in the case of a subject running at 2.5 m in front of the sensor, for different sensor heights.

The system aptness for motion and presence detection application was, therefore, verified.

Future Work:
Design of a readout circuit for a different kind of thermal detector (TMOS)

(Tutor)

Accumulated Credits in the Second Year (10,5):

- Seminars (4): 0,8 CFU
- Ph.D Schools and Intensive Courses (16): 3,2 CFU
- Ph.D Schools Final Exams (1): 1 CFU
- Research Seminars (1): 0,5 CFU
- Publications in conference proceedings (1): 1 CFU
    - DOI: 10.1109/ISCAS.2019.8702506
- Presentations of papers at international conferences (2): 2 CFU
    - "A Chopper Interface Circuit for Thermopile-Based Thermal Sensors" at IEEE Interantional Symposium on Circuits and Systems (ISCAS 2019), 26-29 May 2019, Sapporo, Japan.
    - "An Integrated Micromachined Thermopile Sensor with a Chopper Interface Circuit for Contact-less Temperature Measurements" at International Symposium on Integrated Circuits and Systems (ISICAS 2019), 29-30 August 2019, Venezia, Italy.
- Publications in interantional journals (1): 2 CFU
    - DOI: 10.1109/TCSI.2019.2928717

Accomulated Credits in the First Year (20,5):

- Seminars (21): 4,2 CFU
- UniPV Courses (1): 6 CFU
- Ph.D Schools and Intensive Courses (34 hours): 6,8 CFU
- Ph.D Schools Final Exams (1): 1 CFU
- Didactic Seminars (10 hours): 2 CFU
- Research Seminars (1): 0.5 CFU

Total Accomulated Credits (31)

- Seminars (25): 5 CFU
- UniPV Courses (1): 6 CFU
- Ph.D Schools and Intensive Courses (50 hours): 10 CFU
- Ph.D Schools Final Exams (2): 2 CFU
- Didactic Seminars (10 hours): 2 CFU
- Research Seminars (2): 1 CFU
- Publications in conference proceedings (1): 1 CFU
    - DOI: 10.1109/ISCAS.2019.8702506
- Presentations of papers at international conferences (2): 2 CFU
    - "A Chopper Interface Circuit for Thermopile-Based Thermal Sensors" at IEEE Interantional Symposium on Circuits and Systems (ISCAS 2019), 26-29 May 2019, Sapporo, Japan.
    - "An Integrated Micromachined Thermopile Sensor with a Chopper Interface Circuit for Contact-less Temperature Measurements" at International Symposium on Integrated Circuits and Systems (ISICAS 2019), 29-30 August 2019, Venezia, Italy.
- Publications in international journals (1): 2 CFU
    - DOI: 10.1109/TCSI.2019.2928717