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Noise Study of a Heat Balanced Sigma-Delta Bolometer

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Abstract—The paper presents the modeling of a heat balanced sigma-delta bolometer with Matlab Simulink®. In particular, the noise sources are modeled to enable the evaluation of the output measurement resolution.

Keywords—sigma-delta, bolometer, electrical substitution

I. INTRODUCTION

Bolometers are one type of infrared detector part of the thermal detectors category. A bolometer, illustrated in Fig.1, converts absorbed IR radiation into temperature variation (P/T), which in turn changes the resistance of sensitive layer in the case of a resistive bolometer. The performance of the resistive bolometer is characterized by figures of merit such as its responsivity (\mathfrak{R}) and its effective time constant τ_{eff} [1]. Responsivity characterizes the voltage output variation induced by an infrared optical input. A tradeoff between low time constant τ_{eff} and high responsivity \mathfrak{R} arises from the proportional dependence according to the thermal insulation of those two figures of merit. A bolometer with high thermal insulation exhibits a high responsivity but at the cost of a high time constant.

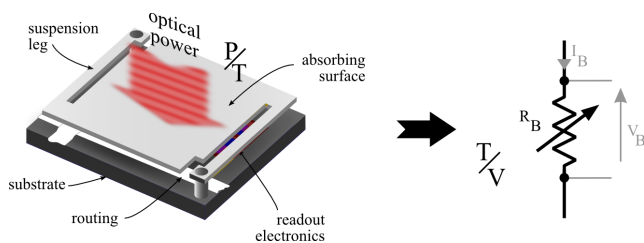


Fig. 1. Top view of a bolometer pixel and equivalent electrical model.

Another limitation of existing bolometer based infrared imaging systems is due to discrepancies between the resistances of the microbolometers during the fabrication process. Discrepancies up to 10% between the resistances of the sensing resistors of an infrared imaging system can occur. This phenomenon is known as spatial noise and can represent up to 10 times the resistance variation due to the measured optical infrared signal. Such spatial noise has to be compensated by calibration and image post-processing. One opportunity exists for the reduction of the time constant of an uncooled resistive bolometer and to overcome the process discrepancies; it consists in the closed-loop mode operation of the bolometer. As for every system, the closed-loop operation of bolometers enables several performance improvements [2] among which the reduction of the time constant and the operation with performance relatively independent of the

performance of the sensor, *i.e.* here independent of the value of the resistance of the sensing resistor. Moreover, advantage can be taken from the feedback configuration to implement smart functions such as self-test, measurement range selection and working point selection [3]. Operating a bolometer in closed-loop assumes that one uses heat feedback means. Such association results into a heat balanced bolometer. Heat feedback means implemented in this paper is Joule power through a digital implementation of the Capacitively Coupled Electrical Substitution [4]. Previous implementation used microcontroller and Pulse-Width Modulated (PWM) signals [4], here a sigma-delta modulator is considered for the generation of the digital feedback signal [5].

Noise study is important for the adequate design of the sigma-delta modulator. Indeed on one hand, the signal-to-noise ratio of the heat balanced sigma-delta shall be limited only by the sensor and not by the conditioning or by the feedback electronics; and on the other hand, over sizing the sigma-delta interface results in higher power consumption, higher silicon surface and potentially higher design complexity. Therefore, this paper presents a model for the noise study of the heat balanced bolometer with a sigma-delta interface. The section II describes the system and the noise sources. The section III details the model used. The section IV illustrates the model through simulation results.

II. DESCRIPTION OF THE SYSTEM

A. Blocks of the System

The heat balanced bolometer system is a closed-loop system as illustrated in Fig. 1. Detailed description of the sigma-delta circuitry and of the closed-loop mode operation can be found in [5] and [2-4] respectively. The system is composed of 6 main parts:

- a sensor, *i.e.* the bolometer,
- the conditioning electronics for the amplification and the filtering, G ,
- a controller, C , that sets the closed-loop performance,
- a sigma-delta modulator, $\Sigma\Delta$, that enables part of the analog-to-digital conversion and generates the digital feedback signal (the bitstream),
- the feedback shaping block, that enables the heat feedback,
- a decimator digital filter that ends the analog-to-digital conversion.

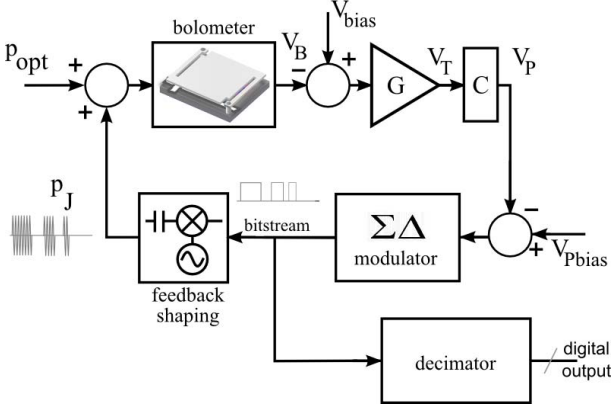


Fig. 2. Schematic of the system.

The system is operating as follows. The sigma-delta modulator with the feedback shaping block constitute the feedback path of the system that compensates for the variations of the input optical power (p_{opt}). The controller, usually integral controller, ensures a stable temperature to the bolometer, defined by the bias voltage V_{Pbias} , by keeping the total amount of power dissipated into the sensing resistor constant ($p_{total} = p_{opt} + p_J$). The Joule power constitutes a direct power reading of the incoming optical power and the decimator filter after the bitstream generates a digital N-bit word. The role of the feedback shaping block is to separate the thermal and electrical bias points. The sigma-delta modulator considered in this paper is the fully-differential, switched-capacitor, 2nd order, single-loop, 1-bit DAC, sigma-delta modulator detailed in [5].

B. Noise Sources of the Systems

The studied noise sources are the ones from the sensor, the noise from conditioning and controller electronics, and the ones of the sigma-delta interface.

1) Noise sources of the sensor

The sensor both exhibits electrical and thermal noises. The electrical noise source of the sensor depends on the nature of the material used for the sensing resistor.

Metallic resistors mainly exhibit Johnson noise while semiconductor resistors also exhibit additional flicker noise.

The Johnson noise is expressed by

$$S_J = 4kTR_B \quad (1)$$

where R_B is the resistance of the sensing resistor, k is the Boltzmann constant and T the operating temperature.

The Flicker noise or $1/f$ noise is expressed by

$$S_{1/f} = \frac{(I_B R_B)^2 \cdot K_{1/f}}{f} \quad (2)$$

where I_B is the bias current of the sensing resistor, $K_{1/f}$ the flicker noise coefficient which value depends on the material used, and f the electrical frequency.

The thermal fluctuation noise is expressed by [1]

$$S_{th} = \frac{4kT^2 G_{eff} \mathfrak{R}^2}{\eta} \quad (3)$$

where \mathfrak{R} is the responsivity of the sensor, G_{eff} is the effective thermal conductance between the bolometer and its surrounding environment [1], and η is the optical absorption coefficient of the sensor surface.

2) Conditioning and controller electronics

Conventional input referred noise power spectrum densities are used for those blocks. The noise of those blocks is characterized by Johnson and flicker noise respectively expressed by

$$S_{n1} \text{ and } S_{n1,1/f} = A_1 / f.$$

3) Sigma-delta modulator

The main noise sources of the sigma-delta modulator are: the quantization noise, the noise from the front-end amplifier, the kT/C thermal noise and the noise due to clock jitter.

a) Quantization noise

The quantization noise depends on the structure of the sigma-delta converter [6], in particular its order, n (the number of integrators), and on the oversampling ratio, OSR (ratio between the sampling frequency and the desired bandwidth). It is expressed according to

$$S_{q\Delta} = \frac{q^2}{4} \left(\frac{1}{3\pi(2n+1)} \left(\frac{\pi}{OSR} \right)^{2n+1} \right) \quad (4)$$

where q is the quantum step of the digital-to-analog converter of the sigma-delta converter.

b) Fully differential switched capacitor folded cascode

In the studied structure the front-end amplifier is a fully differential folded-cascode amplifier corresponding to the design of [5]. As every amplifier, it exhibits both Johnson noise and flicker noise. Those are expressed respectively by

$$S_{n2} \text{ and } S_{n2,1/f} = A_2 / f.$$

c) Switched capacitor noise

This noise corresponds to the kT/C noise generated by thermal noise sampling at switches of the switched capacitor circuitry and is expressed by

$$S_{kT/C} = \frac{2kT}{f_s \cdot C_s} \quad (5)$$

where f_s is the sampling frequency and C_s the sampling capacitance.

d) Clock jitter noise

Sampling clock jitter results in non-uniform sampling. The clock jitter introduces a noise due to sampling instant uncertainty that also depends on the variations of the sampled signal [7]. The sampling error is expressed by

$$S_{\text{jitter}} = \frac{(2\pi f_{\text{in}} A \Delta\tau)^2}{2 \cdot f_s} \quad (6)$$

where f_{in} is the frequency of the input signal, A the amplitude of the sampled signal, $\Delta\tau$ is the standard deviation of the time sampling uncertainty assumed Gaussian [7].

III. MODELING OF THE SYSTEM

The model is realized with Matlab-Simulink® software. The white noises are modeled with white noise generators while flicker noises are obtained by filtering of white noise.

A. Models of noisy parts

The noise of the sensor is modeled by a diagram shown in Fig. 3. where both the thermal noise and the Johnson noises are obtained with white noise generators. The flicker noise is obtained through filtering of white noise. Same types of blocks are used for the noise of amplifiers (Fig. 4.)

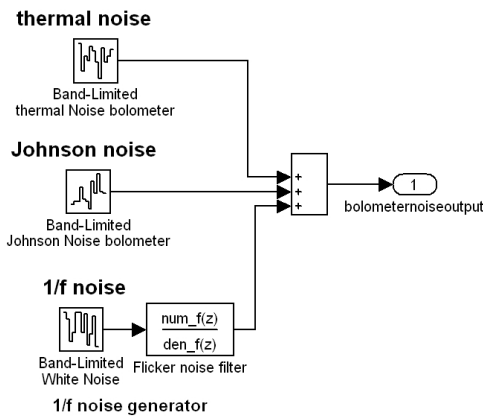


Fig. 3. Noise models associated to the bolometer.

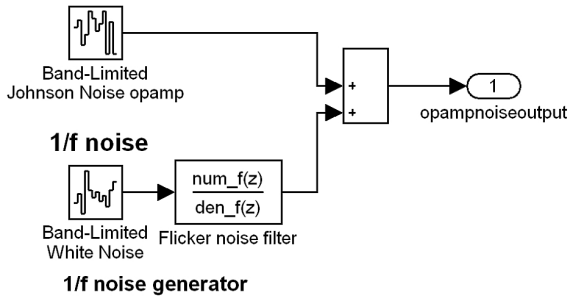


Fig. 4. Noise models associated to the amplifiers.

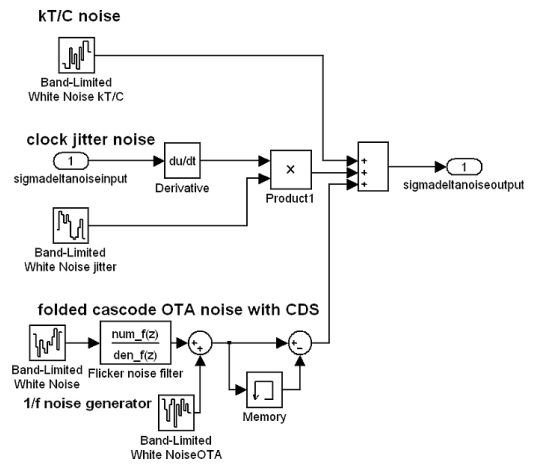


Fig. 5. Noise models associated to the sigma-delta circuitry.

The noise of the sigma-delta circuitry is modeled with the diagram shown in Fig. 5. The Correlated Double Sampling technique (CDS) implemented in the switched capacitor sigma-delta circuitry is taken into account according to its principle, *i.e.* the subtraction of two consecutive noise samples [8]. Such implementation drastically reduces the offset and flicker noise effects on the total noise.

B. Entire System model

The integrators of the sigma-delta modulator are modeled according to [7] as illustrated in Fig.6 with closed-loop unit delay cells.

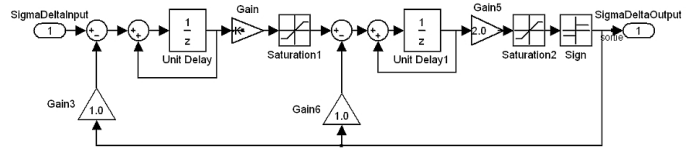


Fig. 6. Schematic of the 2nd order sigma-delta modulator.

The complete model is illustrated in Fig.7. and takes into account the saturation of the electronics stages.

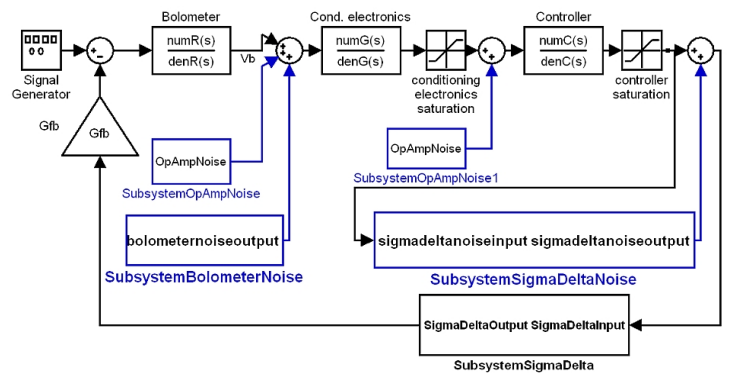


Fig. 7. Diagram of the system.

The noise power spectrum densities of the system are obtained from temporal simulation with Matlab® Pwelch.

IV. SIMULATION RESULTS

The results section illustrates the simulation performed with the model presented. The parameters used for the sigma-delta circuitry correspond to parameters of [5] while the parameters used for the bolometer are typical parameters of microbolometers [9].

Fig. 8 illustrates the effect of correlated double sampling (CDS) of the flicker noise of the front-end amplifier of the sigma-delta modulator. The noise power spectrum density is shaped by the correlated double sampling and noise at low frequency is drastically reduced. Measures performed on the sigma-delta circuitry realized [5] validate this behavior.

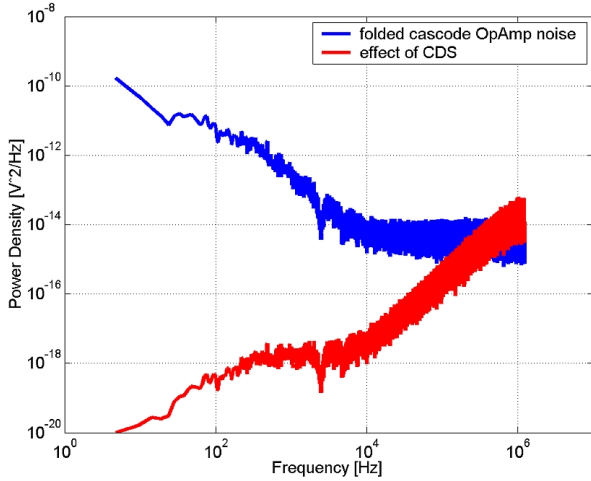


Fig. 8. Effect of the Correlated Double Sampling Correlation (CDS) on the noise of the front-end folded cascode amplifier.

Fig. 9 illustrates the output power spectrum density of the complete heat balanced bolometer as well as power spectrum density taking into account partial contributions of noise. A reference signal with 1 μ W amplitude at 1 kHz is applied at the input of the system during simulation. The sampling frequency is 256 kHz for an OSR of 256 for the measure bandwidth of 1 kHz. The main shape of the power spectrum density is due to the noise shaping effect of the sigma-delta modulator that rejects the quantization noise to high frequencies. The noise of the sigma-delta modulator at low frequencies is dominated by the kT/C contribution. However this contribution is still by design lower than the contribution of the sensor that determines the noise level at low frequencies for the complete system.

V. CONCLUSION

A noise model for simulation of a heat balanced bolometer is presented. The noises sources from the sensor and the sigma-delta circuitry are taken into account. Such model is a tool for simulation that enables to determine the impact of the noise sources, of the structure of the sigma-delta modulator and of

the oversampling ratio on the bit effective resolution of the circuit. Measures performed on the sigma-delta circuitry validate the models. Future work will involve measure on the complete system and cross-match with the simulation results.

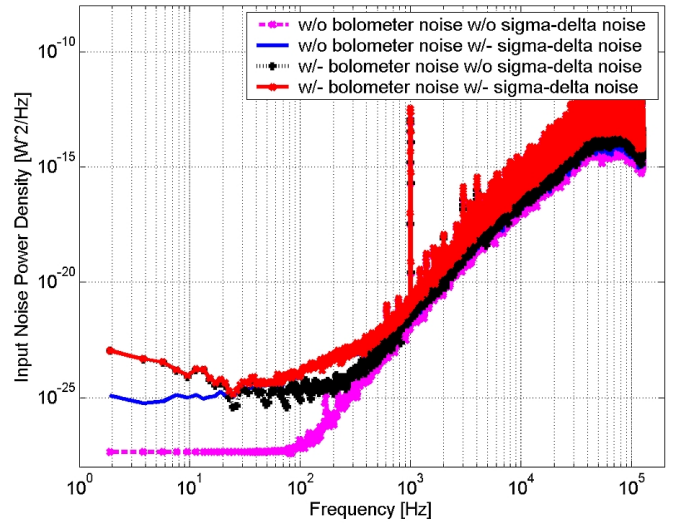


Fig. 9. Power spectral density at the output of the heat balanced bolometer (w/- with ; w/o without).

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