Standard VHDL Modeling and Top-Simulation for the Development of an Integrated Smart-Bolometer

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***Abstract*—An event-driven modeling technique in standard VHDL is presented in this paper for the high level simulation of a resistive bolometer operating in closed-loop mode and implementing smart functions. The closed-loop mode operation is achieved by the capacitively coupled electrical substitution technique. The event-driven VHDL modeling technique is successfully applied to behavioral modeling and simulation of such a multiphysics system involving optical, thermal and electronics mechanisms. The modeling technique allows the high level simulations for the test of the smart functions algorithms of the future integrated smart-device.**

Keywords- top simulation, standard VHDL, smart sensor, bolometer

I. INTRODUCTION

Smart sensors defined according to the IEEE 1451.2 as sensors “that provide functions those necessary for generating a correct representation of a sensed or controlled quantity” [1] are more and more common on the market. These devices integrate on a single chip or in a single package the sensor, its analogous conditioning electronics, some digital electronics for control and data transmission, feedback means, and possibly RF means [2]. The development of such devices combining analogous, digital electronics and physical transducers implies the availability of tools for the design and the validation. Especially, high-level simulation tools are required for the validation of the algorithms implementing the smart functions. Smart functions are for instance self-calibration, identification, or self-test.

From the sensor side, multiphysics design and simulation softwares exist that allow this type of simulation. From the electronics or algorithm side, modeling using VHDL-AMS, Verilog-AMS has been proposed [3]. As far as top validation is concerned, *i.e.* test of embedded algorithms in their operating context, these modeling techniques exhibit huge simulation times that are not compatible with the tuning and optimization of the algorithms and usually suffer from convergence issues. For complex mixed analogous-digital electronics circuits, some designers have an unusual use of the standard VHDL language combined with mathematical packages to model such mixed systems, and proceed to event-driven simulation. Such simulations prevent the convergence issues and drastically reduce the simulation time [4, 5].

In this work, for the first time to our knowledge, we use the standard VHDL modeling and event-driven purely digital simulations during the design and development of a smart-bolometer for the validation of algorithms implementing smart functions. This work takes place at the beginning of the design and the development of integrated smart-bolometers. The smart-sensors considered consist in uncooled resistive bolometers and the implementation of the capacitively coupled electrical substitution [6, 7] that enables the closed loop operation of the bolometers and the implementation of smart functions.

Uncooled resistive bolometers are one kind of infrared sensors. Among the thermal detectors, resistive bolometers are the most commonly met due to the simplicity of their fabrication process, compatible with the semiconductor industry. Uncooled bolometers represent more than 95% of the market of infrared imaging systems in 2010 and the sales volume is expected to triple by 2015 [8]. In that context, our work is to develop bolometers with self-test, self-calibration and identification function, *i.e.* smart-bolometers.

The paper is organized as follows. The first section describes the detection principle of a resistive bolometer and the capacitively coupled electrical substitution for the feedback. The second section presents the standard VHDL modeling of the system. The result section exhibits some simulation results that illustrate the potential of the standard VHDL modeling technique to validate the functional behavior of multi-domain systems. The results also show that this modeling technique answers the need for high level simulation tools to test the algorithms implementing smart functions. The purpose of such simulations is to validate the functionality of the device not the performances; that is why neither noise nor linearity have been modeled in this work but both could be added if necessary in the future.

II. DESCRIPTION OF THE SYSTEM

The device is a closed-loop system composed of a resistive bolometer, its conditioning electronics and the capacitively coupled electrical substitution feedback part.

A. *Uncooled Resistive Bolometer*

The operating principle of an uncooled resistive bolometer is illustrated in Fig.1. An uncooled resistive bolometer converts absorbed infrared (IR) radiation into heat, which in turn changes the resistance of a sensing resistor. The sensing resistor is current biased. A bolometer

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can be modeled as an IR-sensitive element of thermal mass C_{th} linked *via* a thermal conductance G_{th} to a substrate acting as a heat sink. The performance of the bolometer is characterized by figures of merit such as the temperature coefficient of resistance (TCR or α) of the temperature sensing resistor, its responsivity (R), its specific detectivity (D^*) and its effective time constant ($\tau_{eff}=C_{th}/G_{eff}$, G_{eff} is the effective thermal conductance and depends on G_{th}) [9]. The responsivity describes the variations of the output voltage signal ($v_{Tbolometer}$) depending on the IR input radiation ($p_{\text{radiation}}(\omega)$) and it is expressed by the transfer function of the bolometer as follows

$$R(\omega)[V/W] = \frac{v_{T_{bolometer}}(\omega)}{p_{radiation}(\omega)} = \frac{\alpha\eta I_{BIAS} R_B}{G_{eff} + j\omega C_{th}} \qquad (1)$$

where η is the absorption coefficient of the absorption layer of the device, I_{BIAS} is the bias current, R_{B} is the bolometer resistance (sensing resistor). The design of a resistive bolometer results from a tradeoff between responsivity and time constant, under fabrication constraints. Improved responsivity is obtained with small thermal conductance, but this negatively impacts the time constant.

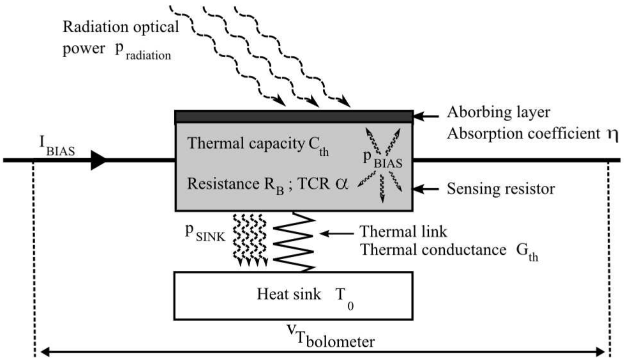


Figure 1. Schematic of a resistive bolometer. The incident IR power is absorbed and converted into heat. The heat rises the temperature of a temperature sensitive resistor thermally coupled to a heat sink at T_0. The resistance change of the sensing resistor is measured.

B. Feedback technique

A way to overcome this trade-off is to operate the bolometer in closed-loop mode. In that case, usually Joule heat is used as feedback means and technique is referred to as electrical substitution [10, 11]. Three techniques of implementation exist for the closed-loop operation:

(i) Direct feedback [12, 13] suffering from stability issues,

(ii) Feedback using an extra heating source [10, 11],

(iii) Capacitively coupled feedback on the sensing resistor [6, 7] that combines the advantages of the two previous solutions. The digital implementation of the capacitively coupled feedback technique, used in this work, is illustrated in Fig.2 and described in details in [6, 7].

The principle is to dissociate the electrical and thermal working points according to a frequency basis. It consists in the use of a high frequency modulated signal for the heat feedback voltage applied to the sensing resistor. This implementation can be applied to any kind of uncooled resistive bolometer. The digital implementation, involving pulse width modulation (PWM) or Sigma-Delta modulation, enables the linearization of the feedback path as well as a direct digital output power reading [7].

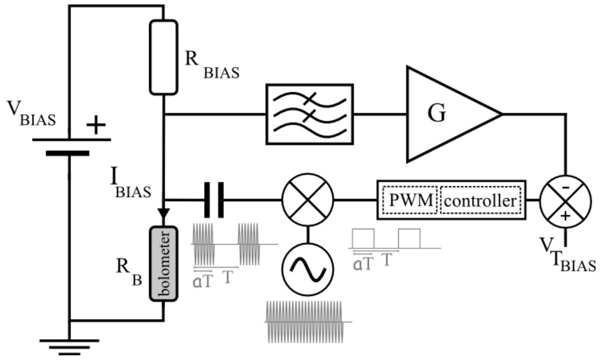


Figure 2. Digital implementation of the capacitively coupled electrical substitution feedback. R_{B} represents the sensing resistor. The feedback is a PWM signal of duty cycle α, translated at high frequency.

C. Smart functions

In addition to the benefits of the operation in closed-loop mode (*e.g.* reduction of the time constant, operation at a defined working point, improvement of the measurement dynamics), the feedback path enables smart functions. This has been extensively studied for in the case of accelerometer or pressure sensor [14]. The basic smart functions of a smart sensor are self-test, self-calibration or autorange. Identification in open and closed-loop is another smart function that enables the monitoring of the aging of the sensor. It consequently allows the update of the feedback controller. Those smart functions correspond to algorithms implemented in the digital part of the smart sensor. The main objective of the standard VHDL modeling is to dynamically test and validate algorithms in their operating context, *i.e.* the mixed analogous-digital and multi-domain high level context.

III. MODELING TECHNIQUE

Advantages of the presented modeling technique come from: (i) the event-driven nature of the simulation using purely digital environment and (ii) the properties of the standard VHDL language. The event-driven nature of the simulation results in drastically shorter simulation times compared to time-driven simulation using for instance Spice or Matlab-Simulink [15]. Using existing digital simulation software (ModelSim, NCSim,…), this modeling technique does not suffer from the convergence issues usually observed with other techniques. The standard VHDL syntax with user's defined types enables implicit connectivity check between the parts of the designed system as in VHDL two connected signals must have the same type.

The basic principle of this modeling technique is the digitalization of the analogous parts of the design. The appropriate modeling of the analogous parts of the design enables to overcome the problematic induced by different time scales. It is the case in this work involving low frequency thermal phenomena (< kHz), and high frequency

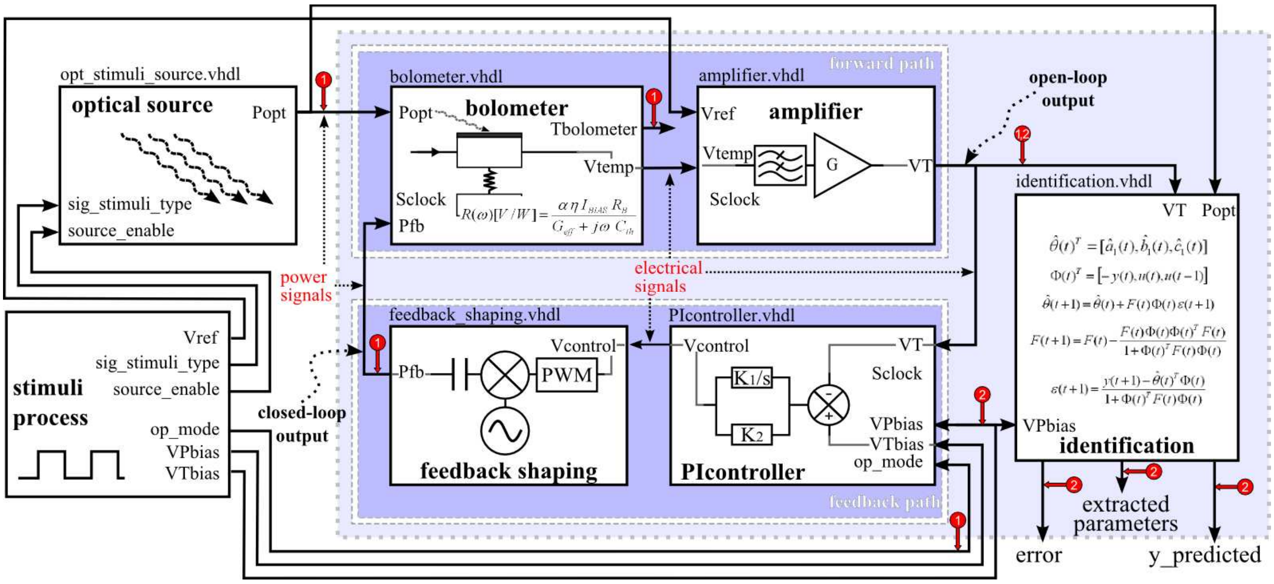


Figure 3. : Block diagram of the complete testbench. The filled box with dotted border represents the smart-bolometer to be integrated, *i.e.*: the sensor itself, the conditioning electronics, the heat feedback and here, as an example of smart function, an open-loop identification function. The circle marked arrows indicate the signals observed in the simulations 1 and 2 presented in the figure Fig.5. All the boxes correspond to standard VHDL files. Sclock is the sampling signal at frequency f_S.

electronics signals due to the modulated feedback signal of the capacitively coupled electrical substitution (MHz range). Those frequency ranges are represented in Fig.4. In the model developed, the phenomena are treated differently depending on their frequency range. Low frequency phenomena such as power/temperature variations or voltage variations due to the temperature variations are considered as signals. On the contrary, high frequency phenomena, essentially the modulated feedback voltage, are not treated as signals. That means no signals at those high frequencies are generated. The model only takes into account the effective feedback power generated by this high frequency modulated signal, which in case of PWM modulation is proportional to the duty cycle [7]. The effective feedback power applied to the sensing resistor varies in the low frequency range related to the thermal phenomena (system bandwidth in Fig. 4). This modeling enables drastic simulation time reduction. In practice the simulation time step corresponds to the digital sampling period of the system ($T_S=1/f_S$). This sampling period is chosen as a tenth of the closed-loop time constant. Consequently, it allows a one-thousand reduction of the simulation time compared to a simulation that would take into account the high frequency feedback signal.

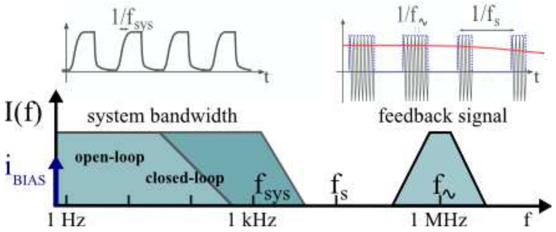


Figure 4. : Frequency domains

All the elements of the system are modeled using standard VHDL. Those elements are schematically presented in the figure Fig.3 corresponding to the testbench. The testbench also includes the optical power stimuli and the stimuli process. In this example, the smart function simulated is open-loop identification.

The model for the bolometer corresponds to the VHDL transcription of the digitalized transfer function (1). The digitalization is achieved using the bilinear transformation. The conversion process is divided into two consecutive steps: (i) the thermal process dealing with power inputs and temperature, (ii) the electrical process corresponding to the temperature measurement. This structure would enable to take into account the electrothermal feedback phenomenon [9] of the bolometer itself if needed in the simulation. At the present time, this phenomenon is taken into account through the use of the effective thermal conductance (G_{eff}) rather than the physical thermal conduction (G_{th}).

The model for the filter and amplifier block only consists in a gain since the bolometer voltage output signal is in the bandpass range of the filter.

The model of the controller in this case implements the equations of a digital proportional integral (PI) controller. The op_mode input enables to choose the operation mode of the controller (open/closed loop).

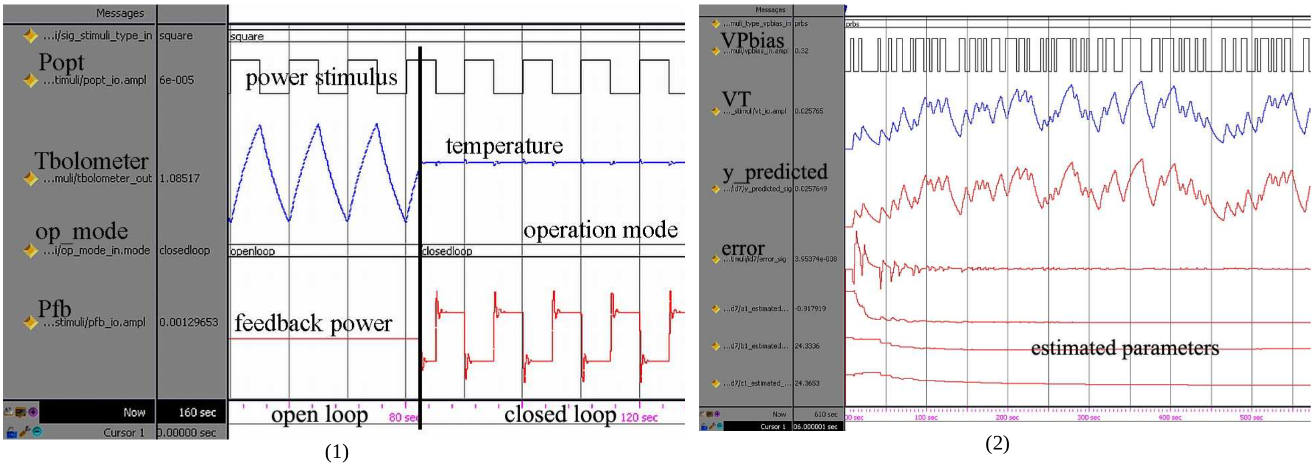
The model for the feedback shaping block consists in a gain and saturations corresponding to the PWM modulation. As mentioned earlier, the high frequency carrier that translates the feedback bandwidth is not taken into account. Only the feedback duty cycle is considered.

The identification block implements a least-mean-square adaptative fitting algorithm which role is to extract parameters in order to optimize the feedback controller and/or to monitor the aging of the device.

The optical source generates stimuli with parameterized frequency, amplitude and shape.

IV. EXAMPLE OF SIMULATION RESULTS

This section illustrates the type of simulation that can be done with this modeling technique. The simulations were performed using the ModelSim Altera 6.3 Quartus II 8.1



(1) (2)

Figure 5. : Examples of digital simulations of the VHDL modelized system.
(1) Open/closed-loop simulation. The simulation begins in open-loop. The square applied optical stimuli (Popt) induces temperature changes in the bolometer (Tbolometer) which is the open-loop ouput. In closed-loop mode, the temperature is regulated as the feedback power (Pfb) compensates the incoming optical power. The closed-loop operation of the bolometer enables a direct power reading of the incoming power through the variations of Pfb.
(2) Open-loop identification process. A least-mean square adaptative algorithm is implemented for the extraction of parameters in order to identify the bolometer characteristics. The predicted output is evaluated with the estimated parameters and the electrical stimuli (VPbias) converted into power stimuli by the feedback path. The prediction error corresponds to the difference between this predicted ouput and the open-loop ouput signal (VT). According to the error the estimated parameters are adjusted. The stimuli is a pseudo random binary sequence (PRBS) in order to optimize the identification process.

software. Parameters for the sensor and the electronics were taken from [7] and correspond to a macro-scale device.

The figure Fig.5 shows two simulation results. Fig.5(1) corresponds to open and closed-loop simulation of the system. The results are in good agreement with experimental results previously obtained [7]. Simulations in either open or closed-loop are performed without convergence issues within a few seconds. This enables fast parameter optimization for the control through series of simulations.

Fig.5(2) corresponds to simulation of a smart function: the identification of the system. An adaptative least-mean-square algorithm is implemented using standard VHDL to extract the characteristic parameters of the bolometer while stimuli are applied. This simulation underlines the ability of the modeling technique to validate algorithm supporting smart functions in their operating context by top simulation.

V. CONCLUSION

An event-driven modeling technique in standard VHDL is presented for the high level simulation of a resistive bolometer operating in closed-loop mode and implementing smart functions. This behavioral modeling technique is successfully applied to the simulation of such a multi-domain system. It enables fast simulations without any convergence issues. The modeling technique allows the test and validation of algorithms supporting smart functions. It is therefore a useful tool for the development of integrated smart sensors.

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