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Electro-thermal coupling analysis methodology for RF circuits

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In this paper an electro-thermal co-simulation methodology suitable for RF circuits is presented. It circumvents traditional transient simulation drawbacks that arise when signals or magnitudes whose frequencies are separated orders of magnitude are present simultaneously in the simulated circuit. The accuracy of the proposed technique is verified experimentally by comparing simulation and measurements of the thermal coupling between an integrated power amplifier (PA) and a differential temperature sensor embedded in the same silicon die, using a 65 nm CMOS technology.

1. Introduction

Electro-thermal simulation of integrated circuits (ICs) is required for predicting the thermal coupling between different circuits integrated in the same silicon die. It has two main applications: prediction of device mismatch due to thermal gradients (which is used, for example, to estimate the performance degradation of circuits that require a good device matching [2,3]) and estimation of the thermal map at the silicon surface during IC field operation (which is used, for instance, to obtain the reference temperature map when temperature is measured as a test parameter to detect/locate structural defects or to debug a circuit malfunction [1,4,5]).

RF circuits are very sensitive to changes in their device performances: any interference, noise coupling between different sections of the SoC IC (e.g. between the digital and the RF sections or between the various blocks of the RF section) or device mismatch reduce dramatically system performance. Focusing on thermal coupling, the first source of thermal interference between RF circuits on the same die is generated by the electrical DC biasing. Electrical DC signals generate DC temperature gradients on the silicon surface, and may produce device mismatch and performance degradation [7]. This thermal coupling can be predicted with state of the art simulation tools [8]. A more challenging situation appears when the RF electrical signals within the circuit are considered: as the main cause of power dissipation is the Joule effect, (power = voltage × current, i.e. $P = VI$), the spectral components of the dissipated power appear at frequencies different than those of the electrical signals, because the product of V and I signals performs a frequency mixing [9]. In [10] it is shown experimentally how a linear resistor in an IC driven by a sinusoidal signal of frequency f generates a temperature increase in its surroundings at two frequencies: DC and $2f$. Extrapolating this situation to a RF circuit, when it processes a single-tone high frequency AC electrical signal, a DC temperature increase is generated. This phenomenon can be described mathematically as (assuming a sinusoidal excitation)

$$P(t) = V(t)I(t) \tag{1}$$

$$V(t) = A\cos(\omega t) \tag{2}$$

$$I(t) = B\cos(\omega t) \tag{3}$$

$$P(t) = \frac{AB}{2} + \frac{1}{2}\cos(2\omega t) \tag{4}$$

Inspecting Eq. (4) it is clear that a sinusoidal excitation causes a DC temperature increase (first term of Eq. (4)) regardless of the electrical frequency. Note that if the excitation signal is of a high enough frequency (like in RF circuits) the 2ω component of the dissipated power does not produce any thermal coupling to nearby circuits since its frequency value falls far beyond the cut-off frequency of the thermal coupling mechanism, which is reported to be around 100 kHz–1 MHz [11,12].

The situation is more complicated when the RF circuit is driven by a two-tone (or multi-tone) electrical signal. In this circumstance, the Joule effect generates intermodulation products even in linear devices [13]. The dissipated power has spectral components at the frequency equal to the difference of the frequencies of the electrical signals processed by the RF circuit (and its multiples if the device has some non-linear electrical characteristics). When these power

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intermodulation tones fall inside the thermal coupling bandwidth, they generate low-frequency AC temperature signals [14], which couple to nearby blocks, e.g., [15] reports an example of narrow-band systems in EDGE/GSM bands (channel separation can be as small as 25 kHz). In this situation, the Joule effect generates a dissipated power that has spectral components at multiples of 25 kHz, which in turn generate an AC temperature increase with the same spectral content that can affect the dynamic electrical behaviour of nearby circuits on the chip.

In this background, the challenge appears as the gap between the electrical operation frequencies of the analogue circuit and the cut-off frequency of the thermal coupling mechanism increases. In such scenario, classical electro-thermal simulation approaches (based on transient spice-like approaches) become inefficient as huge computation time is required.

In this paper, an efficient electro-thermal simulation procedure for the calculation of the spectral components of the temperature increases at the silicon surface suitable for RF and high frequency analogue circuits is presented.

The basics of the proposed technique are presented in Section 2, where it is compared with other existing procedures. In Section 3 the proposed technique is applied to the electro-thermal analysis of an integrated circuit designed in a 65 nm CMOS process containing a RF power amplifier (PA) working at 2 GHz and a differential temperature sensor. In Section 4, simulated results are validated with temperature measurements using the integrated sensor. Finally, Section 5 draws the conclusions.

2. Principle of the electro-thermal simulation of RF circuits

An electro-thermal simulation process consists in solving simultaneously the electrical equations of the circuit and the thermal equations of the heat transfer mechanism in the IC structure. The inputs of the electrical simulator are the electrical stimulus of the circuit and the working temperature of all the devices and the outcome is the power dissipated by each device. The inputs of the thermal simulator are the power dissipated by the devices and the IC structure, being the outcome the temperature of the different devices. Depending on how these two interdependent processes are executed, electro-thermal simulations can be classified into direct [16] or relaxation [17] methods.

The main novelty presented in this paper is the procedure to obtain the power dissipated by devices. As a proof of concept, we have used this procedure to estimate the temperature increase of some devices in a RF circuit containing a power amplifier (PA) and a differential temperature sensor. The procedures used to obtain the thermal map and to couple the changing temperature into the electrical simulation have been extracted from the state of the art [19,20,21] and will be reviewed along this paper to make it self-contained.

2.1. Efficient RF electro-thermal simulation to extract the power dissipated by devices

Traditionally, transient spice-like tools have been employed for the dynamic electro-thermal simulations of a circuit (e.g. [7], [18]). Pure transient simulations have been extensively used to predict the dynamic thermal behaviour of circuits, either to obtain thermal settling times [7] or to estimate the circuit performance degradation for low-frequency analogue circuits [5,16,17].

In RF circuits, electrical and thermal signals are at frequencies separated by several orders of magnitude from each other. Working in the time domain requires choosing a simulation time long enough to capture the lowest frequency of interest (usually the lowest AC components of the temperature). In addition, the simulation time step must be small enough to capture the highest frequency present in the system (usually the highest electrical frequency applied to the circuit). The combination of long simulation times and fine time steps leads to a significant computational cost in terms of memory requirements and execution time. Furthermore, the calculation of the different spectral components of the temperature requires the use of a Fast Fourier Transform (FFT) algorithm. Low numerical error is a must, which is difficult to achieve when there is a big difference in magnitude between the different harmonic components [9]. Moreover, the FFT algorithm may require uniform temporal spacing. Altogether, leads to long simulation times, considerable numerical error or both.

The analysis of the low frequency local thermal increases caused by the quadratic nature of the Joule effect and its co-simulation with high-frequency electrical circuitry can take advantage of the use of advanced simulation techniques. Such type of analysis are similar to that of down-conversion of RF signals to DC or low intermediate frequencies that are required in direct conversion or low-IF receivers. When applied to a RF circuit, single tone signals produce local temperature variations at DC, and two-tone signals produce local temperature variations at DC and at a frequency equal to the difference between the two RF tones frequencies [9]. High frequency thermal components are filtered-out by the inherent low-pass characteristic of thermal coupling in silicon ICs [11,12]. Therefore, the Joule effect can be considered as a down-conversion mixing and the thermal coupling as a filtering process that translates electrical magnitudes from the RF band to thermal magnitudes at DC and low frequencies, as illustrated in Fig. 1.

The co-simulation required for the thermal analysis of RF circuits can be performed with specific electrical simulators developed for RF circuits for reducing computational costs (memory and running times). Two main techniques exist: shooting methods and Harmonic Balance (HB) methods [22]. Both techniques are available in a variety of commercial simulators. In a shooting method, the simulator first searches for the steady-state of the circuit (i.e., the simulator simulates until operating points behave in a periodic way). Then, it computes the periodic response of the system. Its main advantage is that it can work with highly non-linear circuits and with circuits having sharp signal transitions (such as digital circuits). On the other hand, Harmonic Balance methods work directly in the steady-state frequency domain. It has been reported that this method is more appropriate for weakly to moderate non-linear circuits and for circuits with distributed components [22]. In this work, Harmonic Balance technique is used in order to skip settling times (electrical or thermal) and to directly obtain the sinusoidal steady state.

2.2. Extraction of the dissipated power during simulation in RF circuits

In order to perform and electro-thermal simulation it is necessary to extract the dissipated power of the devices that generate the

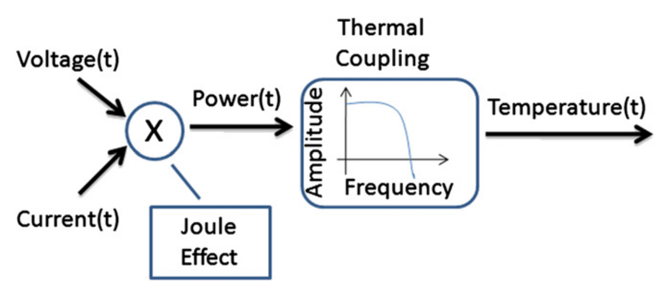

Fig. 1. Frequency domain interpretation of the Joule effect.