Modeling Technique of the Conducted Emission of Integrated Circuit under different temperatures

N. Berbel, R. Fernández-García, and I. Gil

ABSTRACT

In this paper the temperature impact on conducted emissions of ICs up to 3 GHz has been analyzed. The electromagnetic conducted emissions of a commercial IC clock generator have been characterized and modelled from 293 K to 358 K. A temperature parametrized lumped-electrical equivalent model including the PCB and IC behaviour has been developed and validated by means of Feature Selective Validation. The results show that the passive distribution network is slightly affected by the temperature, whereas the IC conducted emission presents a clear temperature variation.

KEY WORDS ICEM-CE, integrated circuit, EMC, internal activity, FSV, conducted emissions, temperature

I. INTRODUCTION

Recently, due to the increasing complexity and miniaturization of microelectronic components, rising frequencies and bit rates, the demand to characterize the electromagnetic compatibility (EMC) at integrated circuits (IC) level has been increased. In fact, the electronic industry requires electrical models to predict conducted or radiated emissions as well as signal and power integrity at IC level [1]. The EMC models can be used either within the IC design phase or with measurements on an existing chip, to predict the impact of the conducted and / or radiated emissions to other electronic ICs.

The “Integrated Circuit Emission Model” (ICEM) was proposed by the International Electro-technical Commission (IEC) [2]. The model predicts the conducted emissions of commercial ICs within the frequency range of 150 kHz to 1 GHz. The model is based on two blocks: on the one hand the passive distribution network of the IC (PDN IC) and the other hand the internal activity (IA). The PDN IC takes into account the characteristics of propagation path of electromagnetic noises (i.e. the path interconnecting the package and the die). The IA models the electromagnetic noise source that originates on switching of active devices in the IC (it includes the contribution of all internal current flowing through the power supply pins). In addition, the passive distribution network of the PCB (PDN PCB) is usually considered as an external block to include the features corresponding to the propagation paths of the PCB traces.

The Integrated Circuit Emission Model – Conducted Emission (ICEM-CE) has been revealed as an excellent model to predict the conducted emissions and it has been used in several works and

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applications [3-5]. According to current International Technology Roadmap for Semiconductors, the future generation of processors are expected to run beyond 10 GHz [6]. Therefore the new EMC models should be extended in order to satisfy these requirements. In this sense, some recent works have been addressed in order to extend the emission models beyond 1 GHz [7]. In addition, industries such as automotive, aeronautical and space require ICs with high level of reliability in hazardous environments, along their lifetime. Therefore it is necessary to include some parameters in the emission modelling, such as the temperature, humidity and aging. In this way, some papers have already been published to evaluate the electrical stress on electromagnetic emissions of IC under different conditions [8-11].

The aim of the work is to characterize and model the effects of temperature on the conducted emission at IC level up to 3 GHz. This paper is organized as follows. In Section II, the experimental setup and device under test (DUT) are detailed. The measurement results are reported and discussed in Section III. In Section IV a conducted emission model is proposed and validated by means of Feature Selective Validation (FSV) technique [12, 13]. Finally, in Section V, the main conclusions are summarized.

II. EXPERIMENTAL

The experimental setup consists of a two-layer PCB test board whose dimensions are 40 mm by 40 mm and $h=0.55$ mm thickness. The PCB layout has been specifically designed in order to test the conducted emissions of a DS1088 low-cost clock generator, using a commercial Rogers RO4350B, with relative dielectric permittivity $\epsilon_r=3.66$, loss tangent $\tan \delta=0.0037$ and all the conducting layers made by copper with conductivity of $5.8 \cdot 10^7$ S/m. The board presents 6 microstrip traces (Fig. 1) with a characteristic impedance of 50 Ω . Notice that several tapers have been used to match the 50 Ω access ports to the IC terminals. The DUT is 100 MHz square-wave output clock generator without external timing components. The DS1088 has two power supply pins and two ground pins, a power-down pin for power-sensitive applications and the square-wave output. The chip is packaged in a Micro Small Outline Package (μ SOP). The supply voltage has been set to 3 V.

The measurement procedure is based on three steps. First, to characterize the impedance of each microstrip trace without DUT (bare board) in order to extract the PDN PCB. Second, to characterize the input impedance including the DUT to extract the PDN IC. Third, to measure the external voltage with the aim to determine the electromagnetic noise source.

The impedance of the PDN PCB is measured by means of a two port shunt connection method using a Vector Network Analyzer (VNA). This method allows measure impedance over a wide range, by obtaining the S_{21} scattering parameter [14]. The input impedance at the n th-transmission line, Z_n , is calculated according to (1).

$$Z_n = \frac{Z_0}{2} \cdot \frac{S_{21}}{1 - S_{21}} \quad (1)$$

where Z_0 is the characteristic impedance of each transmission line.

To obtain the PDN IC, the S-parameters are measured considering the PCB including the DUT. Next, these parameters are converted to T-parameters, obtaining the $[T_{MEAS}]$ matrix. A de-embedding procedure has to be performed in order to remove the PCB traces effect (defined by the T-parameters of the PDN PCB: $[T_{VCC}]$ and $[T_{VSS}]$) [15]. The PDN IC T-parameters, $[T_{IC}]$, are calculated as:

$$[T_{IC}] = [T_{VCC}]^{-1} [T_{MEAS}] [T_{VSS}]^{-1} \quad (2)$$

Eventually, $[T_{IC}]$ can be converted to S or Z-parameters.

Finally, the external current, I_{EXT} , is measured according to the ICEM-CE standard by measuring the spectrum of external voltage ($V_{EXT}(f)$). A 1Ω resistor is added in the power bus for sensing the current, whereas a 49Ω resistor is used to match the output impedance of the sensing network to 50Ω . From this measurement the internal activity (IA) is obtained following the ICEM-CE standard.

In order to evaluate the impact of the temperature on the conducted emission, the DUT has been enclosed in an oven (Fig. 2). The temperature range has been selected from room temperature to the highest value according to the DUT specification (293 K-358 K). Each temperature has been applied to the DUT for 4 hours to settle the DS1088 to the new environment condition. In order to take into account the measurement dispersion ten samples have been tested and statistically processed.

Fig. 1. Designed PCB with a) and without b) DUT

Fig. 2. Experimental setup

III. RESULTS

Figs. 3 and 4 show the experimental average impedance of the power supply traces (V_{CC1} and V_{SS1}) at minimum and maximum temperatures. To take into account the sample dispersion between measurement samples, the 3 times standard deviation ($\pm 3\sigma$) is also shown. As expected, at low frequency higher values of impedance are obtained, whereas at obhigher frequencies the

impedance is decreased. As it is observed, the temperature impact on the PCB traces is low, since a variation of less than 5% along the overall temperature range.

The measured average input impedance and the sample dispersion ($\pm 3\sigma$) including the DUT are illustrated in Figs. 5 and 6. The obtained variation of the input impedance under the considered temperature range is included in the ± 3 standard deviation obtained from room temperature measurements. A higher dispersion of the input impedance of VCC1 terminal with regard of the input impedance of the VSS1 terminal has been observed.

Fig. 7 presents the external current at room temperature and at maximum temperature of 358 K. In both cases, the main conducted emission level is observed at frequencies below 2 GHz. There are some variations in terms of the emission peak frequency and amplitude due to the operation frequency shift of the IC because of the temperature impact. It is observed that the maximum emission level is produced at low temperatures. The maximum measured emission difference between harmonic peaks in all the temperature range is 6.6 dB μ A.

Fig. 3. Impedance of V_{CC1} microstrip trace.

Fig. 4. Impedance of V_{SS1} microstrip trace.

Fig. 5. DUT input impedance through the V_{CC1} terminal

Fig. 6. DUT input impedance through the V_{SS1} terminal

(a)

(b)

Fig. 7: Measurement of the external current: (a) Room temperature (293 K), and (b) 358 K

IV. MODEL AND VALIDATION

To predict the DUT electromagnetic conducted emission under temperature and frequency effects, an equivalent electrical lumped model based on the previous experimental results has been developed. Following the experimental procedure, first the electrical model corresponding to the PDN PCB has been extracted by using a LC circuit according to the transmission line theory [16] in order to expand the model up to 3 GHz. Assuming lossless transmission lines, the main design equations are:

$$v_p(T) = \frac{1}{\sqrt{L(T)C(T)}} \quad Z_o(T) = \sqrt{\frac{L(T)}{C(T)}} \quad (2)$$

Where v_p is the phase velocity, and $L(T)$ and $C(T)$ are the per-section inductance and capacitance of the transmission line unit cells in function of the temperature, T . In fact, as detailed in the previous section, this dependence is low and a constant assumption can be taken into account: $L(T) \approx L$; $C(T) \approx C$. The phase velocity can be calculated from the measured phase of S_{21} ($\phi(S_{21})$) through (3). The parameter l is the transmission line length and f is the frequency at which the lumped model is extracted.

$$v_p = \frac{2\pi l f}{\phi(S_{21})} \quad (3)$$

Each microstrip line section with constant width has been modeled with a number of identical cells, n , determined in terms of the wavelength, by means of (4), where λ is the wavelength at the higher considered frequency (in our case 3 GHz).

$$n \geq \frac{l}{0.1\lambda} \quad (4)$$

The PDN PCB model for the four power supply terminals has been extracted and reported in Table I, considering the average measurement of the samples. Due to the symmetry of the PCB board, the PDN of V_{CC1} and V_{CC2} terminals and the PDN of V_{SS1} and V_{SS2} terminals are identical. The lumped-element inductances and capacitances per unit cell corresponding to the j -trace section are: L_{VCC_j} ; C_{VCC_j} ; L_{VSS_j} ; C_{VSS_j} .

Second, the lumped-element equivalent-circuit of the PDN IC is composed by the following parameters: the inductances L_{11} and L_{22} model the connection path between the package and the die, and R_{11} and R_{22} represent the conductor's ohmic losses. The capacitors C_{11} and C_{22} represent the coupling between the bonding and the ground plane of the IC, whereas capacitors C_{12} and C_{34} model the coupling between the beginning and the end of the interconnection path. The capacitor C_S and the inductance L_S model the metal interconnections within the IC. The capacitor C_{IA} and the resistor R_{IA} model the die input impedance. The inductive coupling between the bonding wires (given by L_{M1} and L_{M2}) has been neglected due to its low impact. The values of the lumped-elements L_{11} , C_{12} , R_{11} , and L_{22} , C_{34} , and R_{22} , are responsible of the two first- resonance, anti-resonance frequencies as well as losses of the input impedance of V_{CC1} and V_{SS1} , respectively. The extracted inductances, capacitances and resistors are reported on Table II.

Finally, the internal activity, IA, models the internal electromagnetic noise source current as a sum of N_H harmonics, according to a fixed current amplitude threshold. For the DUT the harmonics

with amplitude higher than 3 dB μ A have been considered. The IA is modelled by means of its spectral components according to (5).

$$|IA(f, T)| = |C_0(T)| \cdot \delta[f(T)] + 2 \cdot \sum_{n=1}^{N_H} |C_n(T)| \cdot \delta[f(T) - n \cdot f_0(T)] \quad (5)$$

Where C_0 and C_n correspond to the Fourier coefficients, f_0 is the fundamental frequency, $\delta(f)$ is the DC component and $\delta(f - n \cdot f_0)$ the harmonics at multiple of f_0 . The Fourier coefficients, fundamental frequency, the DC component and the harmonics are temperature dependent. The temperature dependence of C_n , has been interpolated from the experimental results according a second order polynomial.

The proposed electric model for the overall system (including PCB and DUT effects) and the temperature impact is depicted in Fig. 8. In order to analyze the model accuracy, the input impedance measurements at V_{CC1} and V_{SS1} have been compared with the corresponding electrical simulations. As shown in Figs. 9 and 10, the model is accurate up to 3 GHz.

TABLE I. CAPACITANCE AND INDUCTANDE ELEMENTS OF PDN PCB

PCB Trace	Length	Width	Number of cells	Component	Value	Component	Value
$V_{CC1,2}$	9.50 mm	1.20 mm	2	L_{VCC_1}	0.80 nH	C_{VCC_1}	227.70 fF
	5.90 mm	0.40 mm	2	L_{VCC_2}	1.02 nH	C_{VCC_2}	76.90 fF
	5.10 mm	1.20 mm	1	L_{VCC_3}	1.06 nH	C_{VCC_3}	200.00 fF
	1.30 mm	1.50 mm	1	L_{VCC_4}	2.64 nH	C_{VCC_4}	54.00 fF
$V_{SS1,2}$	9.52 mm	1.20 mm	2	L_{VSS_1}	1.00 nH	C_{VSS_1}	200.00 fF
	5.63 mm	0.40 mm	2	L_{VSS_2}	0.98 nH	C_{VSS_2}	63.50 fF

Fig. 8: Complete electrical model of the PCB and DUT.

Fig. 9. PCB and DUT input impedance through the V_{CC1} terminal

Fig. 10. PCB and DUT input impedance through the V_{SS1} terminal

TABLE II. VALUES OF THE PDN IC COMPONENTS

Component	Value	Component	Value
L_{11}	1.50 nH	R_{IA}	2932.50 Ω
L_{22}	2.00 nH	R_{11}	3.46 Ω
C_{11}	1.00 pF	R_{22}	6.00 Ω
C_{22}	302.92 fF	L_{M1}	0.00 nH
C_{12}	10.00 pF	L_{M2}	0.00 nH
C_{34}	10.00 pF	L_S	68.30 pH
C_{IA}	21.10 pF	C_S	15.00 fF

In order to validate the proposed emission model, two arbitrary temperature values (343 K and 353 K) not previously measured have been chosen to predict the conducted electromagnetic emission. Next, the electrical simulation results have been compared with the experimental values of I_{EXT} (Figs. 11 and 12) by using the Feature Selective Validation (FSV) technique. The results of the FSV are shown in Fig. 13 for both validated temperatures. It can be observed that the proposed emission model predicts most cases as good and very good.

Fig. 11: Simulation of the external current: (a) 343 K and (b) 353 K

Fig. 12: Measurement of the external current: (a) 343 K and (b) 353 K

Fig. 13: Confidence histogram of the GDM obtained from the FSV analysis of the external current measurement and the proposed model external current for 343 K and 353 K.

V. CONCLUSION

This paper addresses the study of the temperature impact on conducted emissions of ICs up to 3 GHz. The electromagnetic conducted emissions of an IC clock generator have been characterized and modelled in terms of a temperature range (293 K- 358 K). The electrical model takes into

account the PCB distributed effects, packaging high frequency issues and an alternative approach to model the internal current activity. The observed results show that the PDN PCB and PDN IC are slightly affected by the temperature, whereas the IA presents a clear temperature dependence.

The Feature Selective Validation (FSV) standard technique has been used to validate the proposed electrical model at different temperatures. The FSV confirms the feasibility of the model to predict the IC emission.

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BRIEF BIOGRAPHY

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