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DUAL EXPERIMENTAL APPROACH FOR THERMAL IMPACTS ON ELECTROMAGNETIC BEHAVIOR OF ELECTRONIC CIRCUIT BOARD CONFIGURATIONS.

Abstract : Some effects of physical parameters like temperature on electromagnetic emission or susceptibility of electronic circuit boards are non-negligible and can be enforced by new integrated complex electronic structures. These works describe experimental improvements proposed on near-field and radiated mode test setups including temperature parameter. New experimental investigations and methodology are driven to estimate the real external thermal impacts on electromagnetic behavior and compliance. With pertinent characterization's results, review of wide-band frequency modifications of Electromagnetic Compatibility (EMC) responses on electronic configurations with active digital devices and Printed Circuit Board (PCB) wire network are presented and analyzed.

Keywords: Temperature, Electromagnetic field, Characterization, Printed Circuit Board, Radiated mode, Thermal impact, Test set-up, EMC.

1. INTRODUCTION

For modern circuits reported on multilayer Printed Circuit Board (PCB), electromagnetic behavior and compliances are now well established. Many characterizations and simulations, for conducted and radiated electromagnetic emission and immunity cases, are validated and give good investigation studies and pre-compliance results[1]-[4]. Nevertheless, the constant progress of hybrid electronic integration of systems using mixed integrated circuits, especially for embedded and transport applications, modify the real environment whereas the PCB's are tested. As the volume of integration of these circuits trend to reduce, multiple and new physical conditions of coupling ways and interactions, for example between control-command PCB's configurations and

power chip modules, can become more and more problematic[5][6]. An actual aspect to take in account is the influence of the real closer thermal environment. Effectively, high levels of external temperature are surely present with the proximity of high-density digital integrated circuit, power switching chips and radiators system. For example, the range of temperature from a semi-conductor power integrated switch, even with water cooling, stay about 70°C in the volume, and 115°C near the power chip's cells during nominal operation. As future technological issues are to optimize reduction of the power radiators and heat sink volumes, but keeping high-speed and power switching performances, future high-density integrated embedded power prototypes should probably operate at higher steady-state temperature, as 150°C or 200°C, or more with the use of new semi-conductor material as Sic[7][8]. So, temperature, as usual in other key aspects of electronics, should be considered as an actual and future essential contributor to global EMC behavior of circuits, as we want to demonstrate here with this new experimental approach. In this aim, a new methodology and analysis view procedure, named Thermos-Em, for emission's case, or Thermos-Im for immunity's case, including accurate spatial external temperature on a PCB as a significant parameter, are presented. Applications and analysis on specific test prototypes developed for this to study, focusing on PCB wires and PLA circuits (command circuit), are described and summarized.

2. NEW DUAL RADIATED-THERMAL EXPERIMENTAL SET-UP CONFIGURATIONS

Actual state-of-the art of radiated EMC characterizations, both emission and immunity, can be performed over PCB and integrated circuits with near-field probes sets guided by a motorized scan table and/or TEM cells[1]-[3]. In these two cases, often dedicated PCB's are especially designed, inherently for TEM cell to comply with Standardized Cell Aperture (10cm*10cm) and also to separate inside/outer electromagnetic sources and victims[9][10]. To accede to parametric thermal characterization, we propose modifications of these radiated test setups, with a combination of warming plate solution, up to 250°C, inserted in the near-field or TEM solutions, and spatial on-board temperature measurements.

A. Dual near-field/thermal test set-up description

For EMC characterization topics, E-Field and H-field measurement can be realized over different areas of the PCB and the circuit, with a dedicated probes set like H-spires and E-dipoles. Previous coupled thermal/near-field measurements test bench developed were initiated using commercial H/E probes, which were fixed on a manual X-Y plate[11]. Temperature was acquired with a commercial probe, and was also manually moved on the hot zones. The prototype boards used for these studies are especially designed to resume the elementary architecture of a digital electronic function : active device with its package, DC supply network, I/O network, conductive ground plane. Each of them are considered, in a “EMC point of view”, as essential single contributors of global electromagnetic behaviour and potential couplings actors. Among their physical constitution and materials, and so their frequency band-pass and electrical response, they participate to either in conducted mode or radiated mode. Subsequently, each of these electrical part have also been identified to receive an external heat flow which could arise, from ambient (20°C) to their own forced temperature. Steady state temperature of each zone or electrical parts can be also slightly or mainly different, because of thermal conductive properties : FR4-glass, Cu, Al, Plastic packaging...[12]

These initial characterizations have been achieved to demonstrate a real shift of frequency responses of electromagnetic noise. But as a first promising try, it has pointed on a lack of accuracy and methodology procedure for improved further studies, pertinent modeling information and reproducible characterization campaigns. Preliminary investigations, both leaded on basics CMOS inverter boards modeling solutions, have also confirmed the need of an accurate complementary spatial and dual electromagnetic–thermal characterization[13]. From these conclusions, new objectives for improvements of near-field measurement techniques have been proposed and performed to initiate a new configuration of near-field test bench, with the following actions :

- 1) use of a XYZ scan table, with good stability, spatial shift (30cm) and resolution (10µm). The mobile arm is step-by step controlled in each 3D axis. Special design for this table has been studied

and realized in Z direction, to allow the insertion of the warming plate, which volume occupancy is about 22cmx30cmx12cm, below the arm fixture. Z position and reference can be adjusted and hold, in respect to the test PCB minimum distance (1.5cm) to provide efficient heating avoiding destructive burning contacts.

2) designing new scan table probe' system. Electromagnetic probes have been fabricated with high-frequency semi-rigid coaxial cable. Characterization resolutions are driven by a 0.3mm diameter for H-spire, 1cm length for E-probe. For dealing with both thermal measurements, we use a thermal contact probe, with a touch-end of 0.1mm diameter and a thin body support of 8cm long, illustrated in figure 1. We wanted that this probe can be moved over different areas of the PCB, in same time as electromagnetic measures. It has been coupled on the same scan table moving fixture, with a different Z-axis reference. When moving and positioning the measurement point, thermal probe stays in contact with the body of the electric element as near-field probes are just over.

Electromagnetic responses are collected in frequency domain, as H or E levels in dB. Temperature responses, with a more long time constant and variation, are collected by sampling acquisition system. Finally, as the characterization is realized with the active circuit in normal operating mode, supply amplitudes and functional chronograms are controlled during the test by digital wide-band oscilloscope and acquisition boards, which complete all the global new test-setup system[13], represented at the figure 2.

B. New TEM cell thermal parametric test set-up and PCB's associated.

New approach for thermal parametric measurements are also realized with special TEM Cell configurations completed by the thermal experiment solutions. This equipment, also called Crawford Cell, is commonly used for EMC characterization, from 1MHz up to 3GHz, at PCB and Integrated Circuits levels[1][3]. As a well-suited alternative to large size experimental equipment for conventional radiated far field characterization, it allows very pertinent solutions for selective electromagnetic characterization of single electronic devices enclosed in the shielded Cell environment. For this, specific Printed Circuit Boards have to be designed, with the dimension of

the aperture cell, the completion of shielding quality of the system with a one-face metallic plane, and the choice of inside-components to be coupled with Cell Septum in TEM modes.

Starting from this conventional configuration, figure 3 shows the first modification proposed by placing The TEM Cell aperture zone just over the heating area of the warming plate. Inside-cell chip's emissions are collected with a 21Ghz spectrum analyzer on one port of the cell, the other port is loaded by a 50 Ohms HF impedance. Also, a wideband generator associated with 10W amplifier system can be used on one port of the TEM cell, instead of receiver system, to drive aggression for device immunity characterization test. For these two configurations, the TEM cell with its test PCB has to be maintained over maximum 4 cm of the warming plate to keep efficient heating action. It 's realized by a special fixture arm, the constraint is to report electrical and thermal connections very close to the PCB, and to go at the control-measurement system with a 90° angle so as to not touch the hot warming plate.

The second important development proposed for this topic is to achieve an acquisition of the real temperature value on the board. Effectively, the TEM cell configuration don't agree with an external contact thermal probe solution, as used for the surface near-field configuration described previously. To overtaking this, we propose to place directly on new PCB prototypes integrated thin thermal probes using thermal resistor principles, as Resistor Thermometric Device (RTD), and realised in Surface Mounted Device (SMD) technology, or Thin Film technology. As illustrated in Table 1, the choice of RTD material was oriented to Platinum resistor, for good compromises with physical and electrical performances. As we want to place some platinum RTD probes on the external layers of a PCB, we have to deal with two technical constraints to keep thermal performances of these devices. Firstly, we have to realize an accurate acquisition of the equivalent resistance during the heating test. This can be realized with 4wires-Kelvin measurements for each probe : a reference current I_{REF} is injected in the RTD, a differential voltage measurement V_M on the RTD give the equivalent value of resistance :

$$R_T = V_M / I_{REF}$$

with V_M in Volts(V), I_{REF} in Amperes(A) and R_T in Ohms (Ω). The value of I_{REF} should be less than 3mA to avoid self-heating, but sufficient to keep sensitivity in resistor's variations. We choose a nominal stable current value of 1.5mA, injected by the way of an current generator circuit based on a temperature controlled Zener diode schematic. Both current I_{REF} and voltage V_M are controlled and measured by a versatile digital acquisition board, with a $6^{1/2}$ digit accuracy and a 22-bit internal ADC. So maximum discrepancy of measured value of equivalent resistance of the RTD is less than 0.01 Ω . Calibration and calculations of value of temperature for each on-board RTD sample is done with the expression of Callendar-Dusen, for Platinum material resistance [12] :

$$\text{For temperature } < 0^{\circ}\text{C} : \quad R_T = R_0[1 + A \times T + B \times T^2 + C \times T^3 \times (T - 100^{\circ}\text{C})]$$

$$\text{For temperature } > 0^{\circ}\text{C} : \quad R_T = R_0[1 + A \times T + B \times T^2]$$

where T is the temperature value in Celsius degrees, R_T is the resistance value at temperature T, R_0 is the resistance value at 0 $^{\circ}\text{C}$, and A, B et C are numerical coefficients depending of Thermal Resistors technology. Starting from initial values of these coefficients given by RTD constructor datasheets, a calibration procedure is realized with three to five reference temperatures to refine the value of R_0 , A, B et C. Figure 4 represents the temperature variations for three on-board thermal probes when excited by different reference temperature hot points, and confirm the good calibration procedure realized. Finally, experimental temperature value error can be evaluated about a maximum of 0.4 $^{\circ}\text{C}$, which is sufficient for the thermal evaluation sensitivity on our applications.

The second constraint is to place SMD thermal resistors either on conductive or dielectric parts on PCB, as illustrated in figure 5. Dielectric zones are typically the Plastic package of integrated circuit, or Epoxy material of PCB. Conductive parts are typically copper tracks and planes, or circuit package pins. A use of dielectric thermal management adhesive is necessary to both set the thermal SMD device and to ensure a maximum heat transfer. Then, a specific routing to electrically connect each probes to their Kelvin-wires has to be designed and optimized to avoid more unwanted radiated noise or parasitic couplings. For dual thermal / electromagnetic characterization at this level, it is a safe precaution even if thermal measurement system is DC excited and

equivalent resistance's variations have a very low time constant response compared to electromagnetic signal. For TEM Cell configuration, inside cell probes are connected through to the outer with via-hole techniques.

With these developments on new specifications for test prototypes boards techniques, we can have access, on a double layer PCB, to a discrete equivalent thermal scan. With some finite number of temperature points dependant of the study zone considered, and on the different layers, up and down, of the test PCB, we can link and rely it to electromagnetic procedures characterization, and propose new complete modified EMC bench, as illustrated in figure 6.

3. RESULTS AND ANALYSIS OF THERMAL-ELECTROMAGNETIC CAMPAIGN CHARACTERIZATION

With the advances of improved characterizations and techniques described, a new global dual thermal electromagnetic campaign has been initiated. It has started with four kinds of new PCB prototypes, called TEB (Thermal-Electromagnetic-Board) planned to be developed, so as to review all the EMC- temperature impact cases for different electronics configurations concerned by :

- TEB_PAxx : for couplings behaviour of PCB wire pattern (<10GHz)
- TEB_EAxx : for physical/behavioural analysis and modelling on digital circuits
- TEB_CAxx : for command circuit as CPLD/FPGA chip emission and immunity cases
- TEB_POWxx : for high power/smart power on PPCB (Power PCB) emission cases

The actual state of some works engaged with different configurations are resumed in the table 2. Electromagnetic disturbances issued from these boards are observed or attended in the range of 1MHz-1GHz for frequency spectrum repartition. Levels of emissions can reach 5 dBm (smart power cases), and immunity cases can occur with -10dBm of aggression levels (harmonic case, low-voltage circuits).. Global and partial warming in different zones of the PCB considered have been realized, in the range of 24°C to 180° C, in respect with nominal operation of the electronics function. This measurement campaign should confirm, since previous works[11][13], significant shifts of radiated energy levels on wide band frequency with increasing temperature, and subsequently new emissions and immunity thresholds, to be considered for PCB's and Ic's EMC

analysis. Another new challenge with this new approach is to deal with the complexity of multi-parameters characterization processing. Near-field scanning method, both emission and immunity, already needs to represent different parametric values in same vector, as amplitude versus frequency, with spatial(XYZ) and type (E/H) conditions. So, this work presented is also to propose to add new parametric conditions on this data processing, with spatial position temperature and amplitude value, combined with initial near-field data's, in 3D figures. A specific roadmap procedure has been established, for sweeping all complex cases during the characterization. A computational algorithm, for driving, storage and post-processing characterization data has been realized with Computer aided tools for these objectives, and complete all the technical characterization set-up's developed [13].

We present main pertinent results based on two specifics applications boards and formal dual thermal-electromagnetic behavior to analysis: wide-band frequency couplings with PCB wires, and EMC behavior with Programmable Logic Array technology with CPLD circuits.

A. Application on copper wire pattern couplings.

Main EMC disturbances cases are driven by wires, which among their electrical impedance and dimensions, act as parasitic antenna for emission or parasitic coupling ways for immunity. As reported in Table 2, a specific test board, WBTC_1, with a micro-strip configuration, has been modified to review influence of temperature on PCB's wire couplings. Two thermal integrated probes have been placed on each end point of the line, 5cm long over a ground plane. Thin film insulator keep galvanic isolation between copper line and thermal resistance. As Characteristic impedance Z_0 of the line is about 87 Ohms, it is not optimized for good transmission and reflection suppression with standardized 50 Ohms equipment impedance, but the first idea is to have new qualitative information on electromagnetic waves coupling with electrical metallic wires. So the three canonical cases, open, short and loaded terminations will be passed in review, until 1-2GHz.

The modified board is placed in thermal/TEM cell configuration, viewed in figure 7. An

harmonic generator can either inject RF signal on one wire point, or on TEM cell port. Loads termination used, in these two configurations, are 50 Ohms. Power levels of injected signal can be swept from 1 MHz to 2.2GHz, and at a maximum of 20 dBm with a 10W RF amplifier equipment. With this first dual characterization try, coupling responses of the TEM cell give some significant experimental information on thermal impact, as resumed in Table III. The coupling gain or factor is the measured power P_{out}/P_{in} of the Septum-line system, in decibel (dB). The Δ Gain is the absolute difference between Gain@Ambient Temperature and Gain@Forced Temperature. Temperature measured on both thermal resistances are quiet similar, with a difference no more than 0.8°C. Table III shows, in the 500MHz frequency range, with a injected power $P_{in}=10\text{dBm}$, some variation of the coupling gain from 3dB to 5dB enforced both at higher temperature and frequency values.

B. Application on canonical elementary command circuit board.

As control circuit boards are used to drive power converter boards designed for well-suited motion or energy supply function, we want mainly with all this study to focus on their real EMC behavior with non-ambient temperature environment. PCB named “TEB_Caxx” prototypes are planned to be designed for this studies, using programmable integrated circuits type for embedded applications, with Pulse Width Modulation program inside controlled by cyclic rate input command. To do this, two special boards using the same device have been used. First, for near-field emission study, a board initially developed for conventional EMC studies[14], with the IC and electrical network up on one layer of the PCB, has been placed on dual thermal –EM near-field bench. The general level of supply is $V_{DD}=5\text{V}$, furnished by a high-speed current switching voltage source, in respect with internal IC consumption time rate. Programmable circuit operates in synchronous mode, with a clock reference of 5 MHz. Two inputs are used to modulate the output square signal, with an absolute cyclic rate from 5% to 46% (Input 2) and inversion mode(Input 3). Signal output is delivered on internal capacitance load (500fF) in parallel to external capacitance load(1pf).

Measurements over different electronic parts of this board have been performed. H-field and E-

field characterization, as in fact a good image of global conducted noise and integrity signal responses, have been collected up to 1GHz with a scalar spectrum analyzer. Then, represented in figures 8 and 9, measurements data have been processed in 3D configuration, so to have a pertinent view on both frequency repartition, fields amplitude and steps of temperature values. With this representation, we can observe the main electromagnetic response of the PCB impedances and resonance's associated to integrated circuit device as the excitation source, with regular maximum peaks levels visible at 90 MHz, 120MHz, 178MHz, 240MHz, 320MHz. From the reference spectrum waveform obtained at ambient temperature, 20-22°C, represented by the first curves starting on the left of 3D figures 8 and 9, new behavior with increasing steps of temperature are visible. Important conclusions can be formulated[15] :

- significant spectra' shifts are observed over the active device package : 10 to 15dB on the main peaks, until 400 MHz.
- non negligible slight shifts are also observed over the short electrical length wires of the test PCB : 5 to 8 dB maximum.
- H-field is quite twice or three times more temperature sensitive than E-field, especially over the active device package. This is due to IC used for these studies which is mainly current switching driven.

Similar effects, as degradation from ambient T° of frequency and amplitude levels for emission and immunity characterization, can be observed with the TEM Cell configuration. A similar programmable device has been placed on one face of the PCB layers with SMD thermal resistors associated. Device inputs and outputs are leaded to the other side of the PCB, grouped and collected by SMA wide-band metallic connectors. TEM Cell is terminated both end by 50 ohms load, one port by a load HF resistor, other port by the equivalent input impedance of a power meter. As we measure the total power collected at the port of the TEM cell, important shifts of 8 to 20dB are observed in the typical emission noise range of this board, 50-800 MHz. It's the similar relative behavior than near-field over board emission characterization. But this specific board operating

with TEM cell configuration is potentially more interesting for next analysis : last demonstrating experimental study of this work is the case of immunity behavior for a configuration PCB with active device. Aggressions for this aspect are double : electromagnetic coupling signals, either harmonic or transient mode, at different frequencies, times and levels, and non-ambient temperature aggression. Main phenomena's observed for susceptibility aspects are generally for digital mode device the modifications of thresholds levels and switching times. This is due to the couplings of external parasitic signals on supply and I/O ports. The result presented in figure 10 has been realized in harmonic mode, replacing the power meter on one port of the TEM cell by a Amplifier-RF source system. Power injection is realized from 1MHz to 1GHZ, with a maximum level of 60 dBm. Immunity control of the device is determined by some observations, with the spectrum analyzer, of output signal quality : Spectral cyclic rate characteristics and switching current consumption. On figure 10, amplitude current switching device, I_{VDD} , is reported with significant harmonic frequency impact couplings, at ambient temperature, in the 100 MHz-800MHz zone. This variation is enforced when increasing, step by step, the external temperature and so the device package measured temperature. This indicates and confirms, as it want to demonstrate, the modifications of switching current performances, and more significantly, a non negligible impact of high external temperature on electrical behavior of the programmable chip under electromagnetic pressure.

4. CONCLUSIONS

A new complete review on EMC evaluations on Printed Circuit boards with digital devices has been proposed. Starting with well-know established techniques of emission and immunity characterizations on electronic devices, new near-field and TEM field measurements have been developed. Excited by a special directive warming set-up added to Near-field scan table and TEM cell configuration, solutions for acquiring spatial value of temperature over PCB zones are described[15]. New PCB prototypes specifications, with on-board thermal integrated probes allow to perform this new approach. Different canonical cases have been tested, using elementary

electronic configurations : copper wire tracks and couplings, digital programmable device and other in progress, starting a new characterization campaign for research study on this topic. In this paper, the first complete review of experimental results confirm the real impact of temperature on conventional emission and susceptibility behavior used for EMC characterizations and investigations : near-field noise responses are very sensitive to increasing thermal environment. Phenomena is reproducible, and can show about 10dB of real shift on frequency and repartition of EM noise energy. Coupling factors and thresholds susceptibility levels have also a different behavior to hot heating. For the amplitude, variations of 10-15db dB maximum can appear, and frequency repartition of radiated fields, is modified even in the high-frequency zones For high stress temperature (110-130°), a global reduction and spreading of the spectrum levels are observed, mainly because of the high modification of the switching modes of different digital chips used. Electrical mobility and technological parameters of chips are very sensitive to the temperature, and so the electromagnetic responses of the PCB architecture driven by active device.

In parallel to the development of this new dual electromagnetic-thermal characterization procedures, first modeling investigations have been started to reproduce the effect of external temperature on EMC characteristics(emission, susceptibility) of a digital PCB[17]. With this modeling completion study, the responsible of the temperature influence on EMC circuits seems to be mainly the semi-conductor part. Weak effects, but non negligible, are due to by passive copper network circuits. The electromagnetic coupling factors, inductive or capacitive types, are also modified by the non-ambient temperature aggression, and new coupling configurations on special PCB are in study. Modeling effort is now on progress to have concordances with EMC simulations and measurements on a range of 20-220° C. This new experimental approach wanted to demonstrate and give confirmation of real impact of external temperature to complete library models works dedicated to EMC, and to drive efficiently future EMC investigations and previsions for electronics integrated chips with embedded hybrid technology and constraints.

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