Radiated Emissions Estimation of an Integrated Circuit Based on Measurements in GTEM Cell

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Abstract — **The International standard IEC 61967-2 describes radiated emissions test of ICs by mounting IC test board on a wall port of a TEM/GTEM cell. Therefore a typical GTEM cell has to be modified to incorporate the wall port. However, apart of additional cost, improper modification affects the measured voltage at the GTEM output port. In this paper, we present an attempt to perform IC radiated measurements inside a GTEM cell followed by employing standard algorithms to verify with measurements in a semi-anechoic chamber (SAC). The results based on GTEM measurement indicate an impressive correlation with SAC measurements and can be improved further for IC radiated emissions measurement in a GTEM cell.**

***Keywords*— IC radiated emission, GTEM, dipole moment, common-mode current, SAC**

I. Introduction

Many studies report the contribution of integrated circuits (ICs) as ultimate noise source of radiated emissions due to new process technology, the constant increase of clock speed, power consumption, circuit density and complexity [1, 2]. Therefore, there are great interests for electromagnetic compatibility (EMC) compliance test at component level [3]. Previous works have established SAE J1752/3 [4] and the IEC 61967-2 [5] documentations as standard procedures to evaluate radiated emission from ICs in the frequency range 150 kHz to 1 GHz using TEM cells and wideband TEM (GTEM) cells. The current practice is clamping IC test board on the cell wall port cut in the top or bottom of the cell so that the IC test board becomes a part of the cell wall. This ensures the IC as the only radiation source in the measurement and the interference contributed by other unnecessary noise sources can be avoided.

According to IEC 61967-2 test procedure, a wall port must be developed at an exact location of GTEM cell for IC emission test. Inappropriate wall port incorporation can affect the measured voltage as it concerned the spacing between the septum to test board. Moreover, the horizontal dimension of an IC typically is much larger than its thickness resulting in the horizontal positioning of the IC on the wall port tends to neglect emission due to the vertical polarization field which has been shown to be relatively significant [6, 7]. It is therefore desirable to develop alternative method to perform IC radiated emissions inside GTEM cell instead of clamping it on the wall port to avoid undesired fabrication error on the measured voltage and to account both the horizontal and vertical polarizations emissions of the IC. For this purpose, several precautions have been taken into consideration during measurement in GTEM cell and validation with semi-anechoic chamber (SAC)

In this paper, we present preliminary results to perform radiated emission measurement of a FPGA test board enclosed in a metallic enclosure and regulated by external power and signal sources inside a GTEM cell. The paper is organized as follows. First, Section II presents the setup precautions to overcome the problems such as field coupling to enclosure and exit cables, disturbance from other supporting components, how to ensure the IC is the only source of the radiated emission test and the device under test (DUT) measurement procedure inside the GTEM cell. Then, Section III describes a standard 6/9 algorithm defined in [8] that uses a set of six electric and magnetic dipole moments where nine measurements are required to extract the six dipole moments for far field calculation. Finally, the calculated fields of extracted equivalent dipole moments are validated using far field measurement in SAC.

II. Setup and Measurements

A. EUT Setup

A FPGA chip represents the DUT was used to conduct emissions measurement. The chip was mounted on a standardized 10cm x 10cm test printed circuit board (PCB) designed according to the specifications in IEC 61967-1. Fig. 1 shows the FPGA chip is the only component mounted on top side of the PCB whereas all supporting components are soldered on the bottom of the PCB. The FPGA chip has 780 pins with two pins utilized for clock and output signals. A toggle flip-flop (TFF) logic circuit was loaded into the FPGA for testing. The clock frequency of the TFF is 100MHz and the output signal is one half of the clock frequency. The differential pair of output signal is terminated with a 50Ω load.

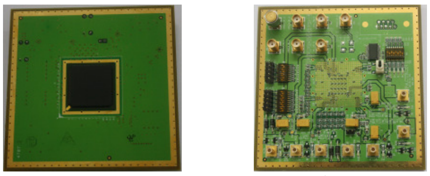
(a) (b)

Fig. 1 IC test PCB (a) top side, (b) bottom side

In the measurement, the entire test board is properly shielded inside a metallic enclosure except the chip which is exposed outside the enclosure through a window. This prevents direct emission from the PCB and other components contaminating the measurement. It is also important to make sure the DUT as the only radiation source. Self-adhesive gasket is placed all sides of the chip to block the gap between PCB and enclosure as well as divert induce RF current on the surface of the enclosure to the PCB ground plane. This can reduce the impact of electromagnetic field coupling between the chip and enclosure to measurement.

All edges of the enclosure are covered with copper tape in order to prevent leakage at the edges. Since cables are needed to connect the external power and signal sources to DUT, it needs to be shielded and the shield of the cables must be connected properly to the enclosure to avoid common-mode radiation. The bulk-head connector is employed to isolate inner and outer environments of enclosure while feeding the external clock and power to the DUT. The DUT setup and the position of the connectors can be seen in Fig. 2.

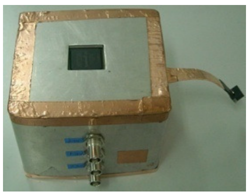

Fig. 2 Setup of the DUT enclosure

In the following sections, we use the term equipment under test (EUT) to replace DUT since the IC is a part of the metallic enclosure. However the metallic enclosure is connected to the ground plane of the PCB, it therefore can be assumed that no radiated field is transmitted from inside to outside of the enclosure. The induced current on the surface of the enclosure have been diverted to ground and the radiated emission test is done on the assumption that the FPGA is the only contributing source.

B. Emission Measurements

For GTEM measurement, the EUT was mounted on a manipulator and rotated around at three orthogonal orientations. The exit cables were freely routed along the test volume in the measurement. At each orientation, the radiated emission was measured in three positions by rotating the EUT at 0, 45 and -45 degrees. Therefore a total of nine measurements were employed to calculate the six dipole moments. As far as the exit cables are concerned as part of the EUT in the measurement, the effect can be neglected because it has been well shielded and grounded. It is assumed that the measured radiation is entirely due to the IC.

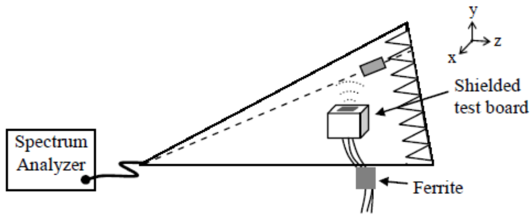

Fig. 3 EUT horizontal emission measurement in GTEM cell

The EUT setup in GTEM cell is illustrated in Fig. 3 where a spectrum analyzer is connected to the cell port to receive the output voltage due to radiation from the IC which coupled onto the septum of the GTEM cell. The monitored frequencies are from 30MHz up to 1GHz.

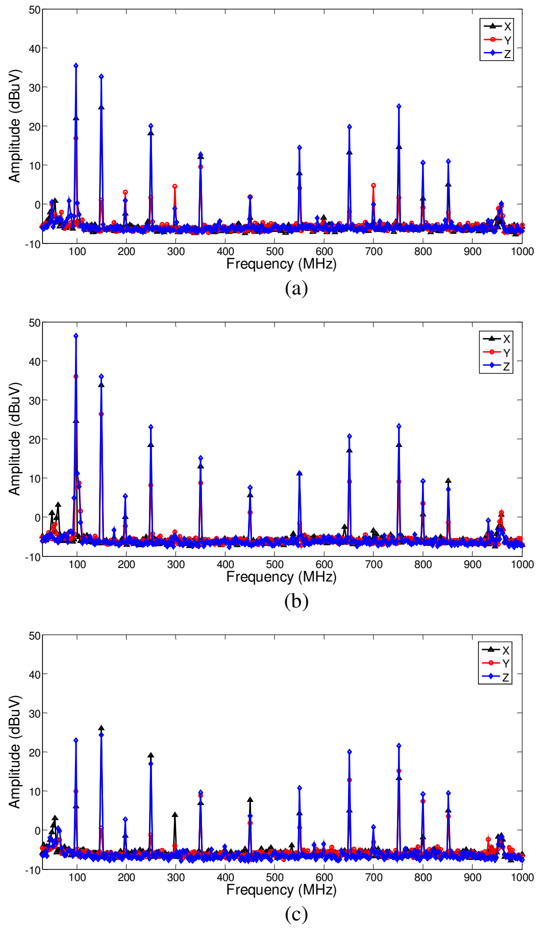

Fig. 4 Radiated emission at three positions of EUT (a) 0°, (b) 45°, and (c) -45°

Fig. 4 shows the measured voltages for the EUT in three different positions. The peak values of the emissions correspond to the fundamental and harmonic frequencies of the clock and output signal. The radiations from both *z* and *x* positions are apparently higher than that from *y* positions. This indicates that noise sources of vertical position is significant and cannot be neglected in the IC emission evaluation.

III. Emission Model

The real radiated far field of the EUT is estimated with the 6/9 algorithm of P. Wilson [8] where a set of orthogonal electric and magnetic dipoles is obtained to represent the emission model of the EUT. The algorithm uses nine GTEM measurements of Fig. 4 to determine the complete set of dipoles given by three electric moments $P_{x'}$, $P_{y'}$, $P_{z'}$ and three magnetic moments $M_{x'}$, $M_{y'}$, $M_{z'}$ to approximate the far-field radiated emissions. The algorithm neglects the phase differences between the six moments. The voltage in decibels per microvolt (dBμV) is first measured at the GTEM cell port and then normalized by the TEM mode in backward direction to relate to the magnitude of b_{ij} via

$$b_{ij} = \frac{4\times 10^{\left(V_{ij}(dBuV)-120\right)/10}}{Z_C e_{0y}^2} \qquad (1)$$

with $Z_c = 50\Omega$ is the GTEM cell characteristic impedance and e_{0y} is numerically approximated by

$$e_{0y}(\bar{o}) = \frac{4}{a} Z_c^{1/2} \sum_{m=1,3,5\ldots}^{\infty} \left[\frac{\cosh\left(\frac{m\pi y}{a}\right)}{\sinh\left(\frac{m\pi h}{a}\right)}\right] \cdot \cos(m\pi x/a)\sin(m\pi/2) J_0(m\pi g/a) \qquad (2)$$

where *a*, *h*, *g*, *y* are respectively the cell width, the septum height, gap width, and the test object height all at the measurement location.

The first subscript represents the rotation of EUT in the three basic orthogonal permutations of the cell. The second subscript denotes three rotation angles with $\alpha = 0$, $\alpha = \pi/4$, and $\alpha = -\pi/4$ of each orientation. Thus, the following nine equations correspond to nine measurements are used to calculate six electric and magnetic dipole moments.

$$\begin{aligned}
b_{11} &= P_{y'}^2 + k_0^2 M_{x'}^2 \\
b_{12} &= P_{y'}^2 + \tfrac{1}{2}k_0^2 M_{x'}^2 + \tfrac{1}{2}k_0^2 M_{z'}^2 + k_0^2 M_{x'}^2 M_{z'}^2 \\
b_{13} &= P_{y'}^2 + \tfrac{1}{2}k_0^2 M_{x'}^2 + \tfrac{1}{2}k_0^2 M_{z'}^2 - k_0^2 M_{x'}^2 M_{z'}^2 \\
b_{21} &= P_{z'}^2 + k_0^2 M_{y'}^2 \\
b_{22} &= P_{z'}^2 + \tfrac{1}{2}k_0^2 M_{y'}^2 + \tfrac{1}{2}k_0^2 M_{x'}^2 + k_0^2 M_{y'}^2 M_{x'}^2 \\
b_{23} &= P_{z'}^2 + \tfrac{1}{2}k_0^2 M_{y'}^2 + \tfrac{1}{2}k_0^2 M_{x'}^2 - k_0^2 M_{y'}^2 M_{x'}^2 \\
b_{31} &= P_{x'}^2 + k_0^2 M_{z'}^2 \\
b_{32} &= P_{x'}^2 + \tfrac{1}{2}k_0^2 M_{z'}^2 + \tfrac{1}{2}k_0^2 M_{y'}^2 + k_0^2 M_{z'}^2 M_{y'}^2 \\
b_{33} &= P_{x'}^2 + \tfrac{1}{2}k_0^2 M_{z'}^2 + \tfrac{1}{2}k_0^2 M_{y'}^2 - k_0^2 M_{z'}^2 M_{y'}^2
\end{aligned} \qquad (3)$$

with k_o is the wave number in free space.

Since it is not known whether the EUT is predominant electric ($P >> k_oM$) or magnetic ($P << k_oM$) source, the magnetic dipole moments can be determined by

$$k_0^2 M_{x'}^2 = \frac{D_1 D_2}{2D_3};\ k_0^2 M_{y'}^2 = \frac{D_2 D_3}{2D_1};\ k_0^2 M_{z'}^2 = \frac{D_3 D_1}{2D_2} \qquad (4)$$

with

$$D_1 = |b_{12} - b_{13}|,\ D_2 = |b_{22} - b_{23}|,\ D_3 = |b_{32} - b_{33}| \qquad (5)$$

and the electric dipole moments can be solved by

$$\begin{aligned}
P_{y'}^2 &= b_{11} - k_0^2 M_{x'}^2 \\
P_{z'}^2 &= b_{21} - k_0^2 M_{y'}^2 \\
P_{x'}^2 &= b_{31} - k_0^2 M_{z'}^2
\end{aligned} \qquad (6)$$

Alternatively, the electric dipole moments can be determined by

$$\begin{aligned}
P_{y'}^2 &= \tfrac{1}{2}\left\{(b_{12} + b_{13}) - k_0^2 M_{x'}^2 - k_0^2 M_{z'}^2\right\} \\
P_{z'}^2 &= \tfrac{1}{2}\left\{(b_{22} + b_{23}) - k_0^2 M_{y'}^2 - k_0^2 M_{x'}^2\right\} \\
P_{y'}^2 &= \tfrac{1}{2}\left\{(b_{32} + b_{33}) - k_0^2 M_{z'}^2 - k_0^2 M_{y'}^2\right\}
\end{aligned} \qquad (7)$$

IV. Validation and Result Analysis

For validation, far-field radiated measurements in SAC were conducted to obtain vertical and horizontal radiated emission of the EUT. The EUT is placed at a height of 0.8m above a ground plane of the chamber. The radiated field was measured at 3m distance defined from the centre of the EUT using broadband antenna. Fig. 5 shows an experimental setup while the EUT is in horizontal position. The EUT is placed on a turntable in the SAC which is similar with the GTEM setup. In GTEM, the rotation of the EUT in three orthogonal positions leads to a significant changes of the cable layout. However, the exit cables layouts do not differ much for horizontal and vertical evaluation in the chamber.

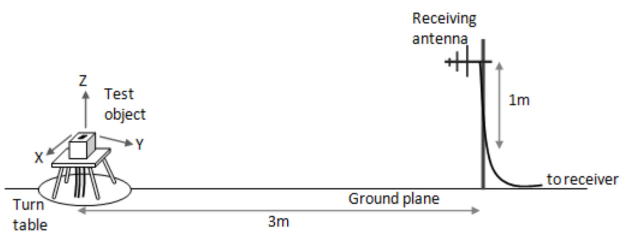

Fig. 5 Radiated measurement in semi anechoic chamber

Fig. 6 shows the measured electric fields in SAC in vertical and horizontal positions as compared with the radiated fields calculated from the extracted equivalent dipole moments in GTEM cell.

Generally, the electric fields measured in SAC are higher than predicted based on GTEM measurement except for frequencies below 200MHz. It is suspected that the exit cables still behave as a source of electromagnetic radiation even though they have been shielded and ferrites have been used [9]. In addition, the inconsistencies of cable layout during GTEM measurement contribute to the discrepancies in the results. It is also believed that the enclosure and cables disturbed the field distribution in the GTEM cell affecting the measured voltages.

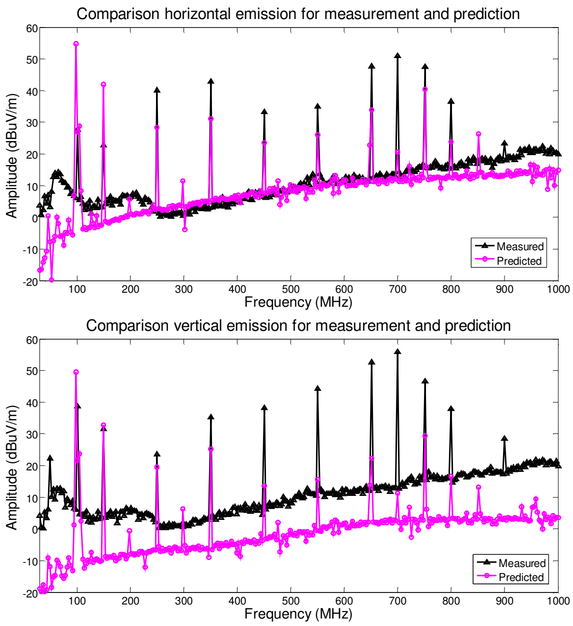

Fig. 6 Comparisons of the radiated fields from measurements with calculation from the extracted dipole moments

The linear correlative relationships between the measurement and prediction results can statistically analysis with Pearson's *r* given by [10]

$$r = \frac{\sum_i (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_i (x_i - \bar{x})^2}\sqrt{\sum_i (y_i - \bar{y})^2}} \quad (8)$$

where x_i is GTEM data in dBuV/m and y_i is SAC data, and $\bar{x}$ is the mean of x_i and $\bar{y}$ is the mean of y_i. The comparison gives an acceptable correlation as shown in Table 1.

Table 1 Correlation coefficient of predicted and measured fields

	Pearson's *r*
Horizontal field	0.689
Vertical field	0.694

It seems that placing the entire test board in a GTEM cell for radiated emission measurements of the IC need to be carried out with extreme care especially on the existence of common-mode current on the cables and metallic enclosure. However, the results presented in this paper indicate the possibility of improving current practice of IC measurements using GTEM if all possible sources of radiation from unwanted sources external to the IC can be reduced or totally removed.

V. CONCLUSIONS

This paper has presented an approach to perform radiated emissions measurement of IC by placing the entire IC test board inside a GTEM cell and regulated by external sources. In general, a proper shielding of the IC test board and careful setup to avoid ambient interference are crucial to obtain the desired results. It has been shown that a strong correlation of IC emission can be achieved between GTEM and semi anechoic chamber measurements. Further investigation will be conducted to examine the uncertainty in order to improve the agreement between measurement and prediction results.

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