Predicting Module Level RF Emissions from IC Emissions Measurements using a 1 GHz TEM or GTEM Cell – a Review of Related Published Technical Papers

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Abstract: This paper reviews some of the many published technical papers relating to the measurement of IC emissions using a 1 GHz TEM cell or GTEM cell modified to accept an IC test board and provides a basis for correlation between these IC level measurements and module level RF emissions. We will follow the development of this methodology from the early investigations through the later applications to show the viability of the technique for IC qualification. Developments over time have shown that this method of IC emission measurement is repeatable, correlatable to other methods and provides, within limits, useful prediction of module level RF emissions performance.

I. INTRODUCTION

Several technical papers have been written since 1996 to investigate the measurement of IC emissions using a TEM cell where the IC under test is installed on a standardized test board that is mounted to a port on the cell wall. With this arrangement, the test board becomes a part of the wall above the septum of the cell. The intent of the authors was to develop a TEM cell optimized for IC emission measurements that, because of its small size, would have a 1 GHz or higher usable upper frequency. Ultimately, Fischer Custom Communications was able to develop such a 1 GHz TEM cell working collaboratively with the authors. We will look at several papers that illustrate the development of IC emission measurements using this 1 GHz TEM cell and the usefulness of this method for IC analysis. We will also consider the relationship of this method to IC near field scanning and the ability of both of these methods to provide a useful prediction of far field emissions.

II. DESCRIPTION OF THE TEM CELL AND IC TEST BOARD

Figure 1 is a diagram of the cell cross section along its axis showing the 50 ohm feed and load terminations and the IC under test on its test board. Figure 2 is a ¾ view of the 1 GHz TEM cell showing the port with clamps to secure the test board. Figure 3 is a picture of a representative test board with the supporting circuit components mounted on the side that is outside the cell. Figure 4 is a picture of a representative test board showing the IC to be evaluated mounted on the side that faces in to the TEM cell.

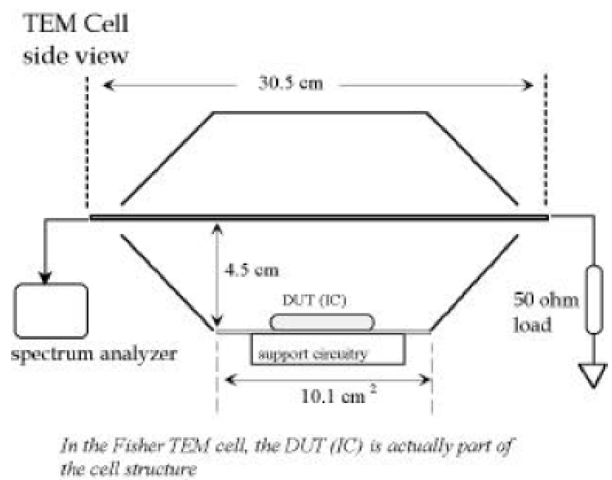

Figure 1 - Cross Section of 1 GHz TEM Cell

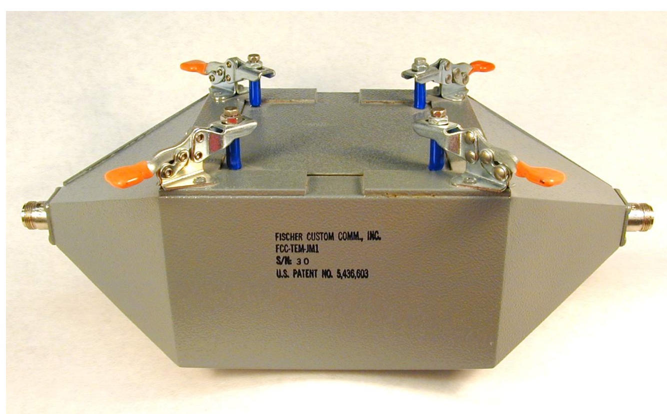

Figure 2 - 3/4 View of 1 GHz TEM Cell

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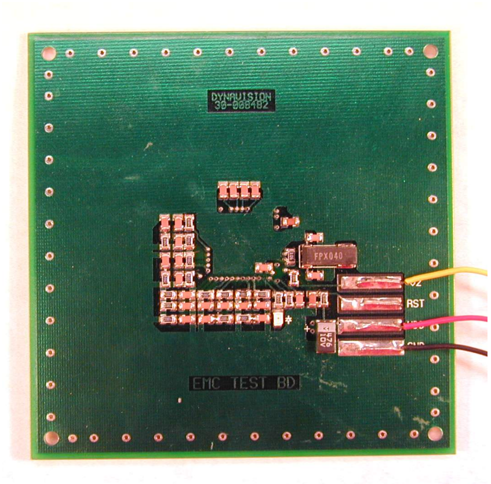

Figure 3 – Component Side of Test Board

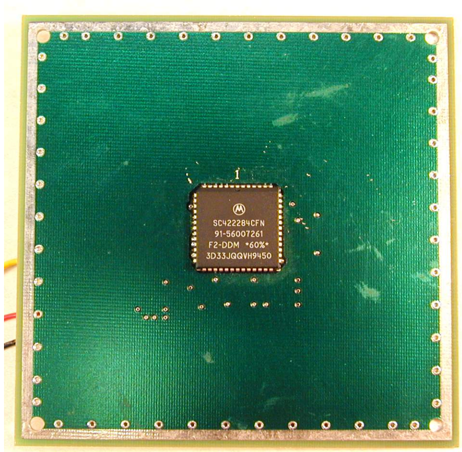

Figure 4 – IC Side of Test Board

III. Development of the TEM Cell Method

During the early development of this method of IC emissions measurement, questions as to the mechanism of coupling between the IC and the TEM cell septum were raised. As a part of our involvement with the development of these procedures, we along with other authors, began investigating theoretical models for this coupling. The hypothesis being examined was that the IC could be modeled as a resultant equivalent current loop.

In the paper *Investigation of the Theoretical Basis for Using a 1 GHz TEM Cell to Evaluate the Radiated Emissions from Integrated Circuits*, by Muccioli, North & Slattery (1996), the authors considered that the use of the Fischer TEM cell to characterize the emission spectra of ICs is enhanced by an understanding of the underlying coupling mechanisms between the DUT and the cell. Therefore, a model of the IC lead frame as a current loop was developed and analyzed for coupling to the septum of the TEM cell at different orientations. Test boards with current loops orientated both parallel and orthogonal to the TEM cell wall were evaluated for correlation with the model. Figure 5 is a comparison of the theoretical model and the measured data.

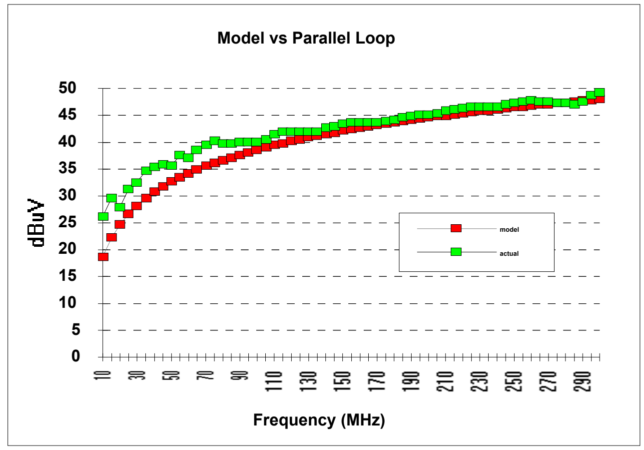

Figure 5 - Comparison of Model (Red) vs Measured Parallel Loop (Green)

Figure 6 shows the effect of orientation of the IC under test relative to the TEM cell. For a 90 degree rotation of the microprocessor test board relative to the TEM cell axis, the spectral output could vary by as much as 12 to 14 dB.

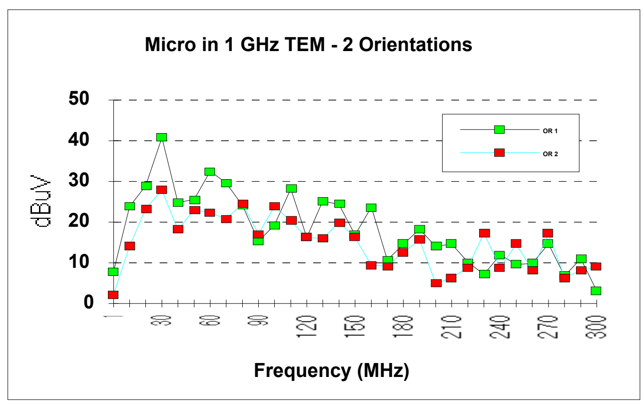

Figure 6 - Two Orientations of Microprocessor Test Board

Using a microprocessor on a test board, a comparison was made of the measured data from the 1 GHz TEM cell, the EMSCAN^{TM} circuit board analysis system and radiated field measurements. TEM cell measurements of a microprocessor on a test board and measurements of the same test board using the EMSCAN^{TM} circuit board analysis system showed close agreement. Figure 7 compares the radiated emissions as measured in an absorber lined shielded room using a biconical antenna at a distance of 1 meter from the microprocessor test board. This received signal was measured on a spectrum analyzer and the peak value at 40 MHz was 43 dBuV. The vertical and horizontal scans differed by about 9 dB.

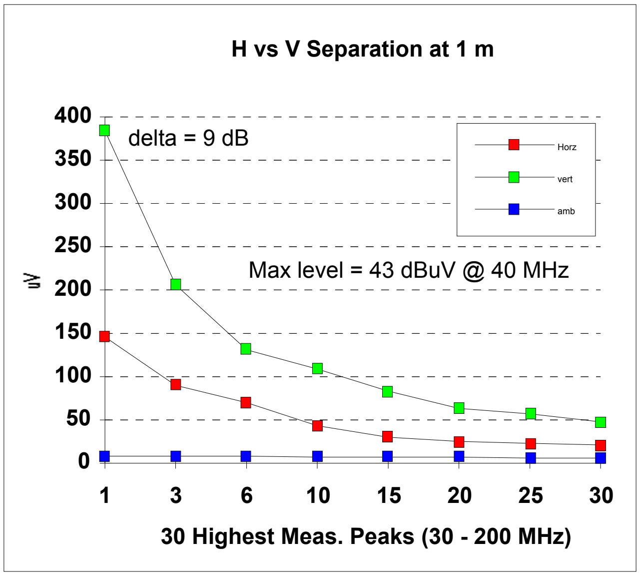

Figure 7 - Measurement in ALSE with Biconical Antenna of Micro Test Board in H and V Orientations

Overall, there was very close agreement for three completely different techniques for evaluating the radiated emissions from a source. Methods for calibration of the TEM cell were also investigated. Investigation of the coupling from simple loop and monopole structures to the TEM cell confirmed the usefulness of the theoretical model, the reciprocity in coupling into the cell or from the cell into the test loop and repeatability of the measurements. Correlation with ALSE measurements indicated the predictive value of the TEM cell for far field emissions of a basic microprocessor test board.

In *Model of IC Emissions into a TEM Cell, Engel (1997)*, Andy Engel of Motorola, presented "a rigorous, full-wave computer model of an arbitrarily oriented IC-like source in a TEM cell." The model presented was described and validated and the radiation resistance of IC-like structures was investigated. Also, the contribution of a switching output port pin to the total IC emissions into a TEM cell was quantified by identifying the signal paths and combining the radiation resistances with SPICE based Fourier transforms of the currents.

IV. Evaluation of IC Process Variables

A more in depth look into the effects of IC process variables on RF emissions was presented in the paper *Characterization of the RF Emissions from a Family of Microprocessors Using a 1 GHz TEM Cell, Muccioli, North, Slattery (1998).* Our assumption was that IC process variations, particularly those that impact on internal rise time, can have a significant effect on the RF emissions from a microprocessor. The authors looked at the internal rise time of the IC die, the IC clock rate, the IC I/O rise time, the IC die level and IC fabrication (fab) process variations in their study. In our investigation, we observed significant variations in the RF spectra due to IC die level and IC fab location and process. Figure 8 presents spectral data, filtered using a 16 point moving average, for the eight micros representing the four process corners from two different fabs.

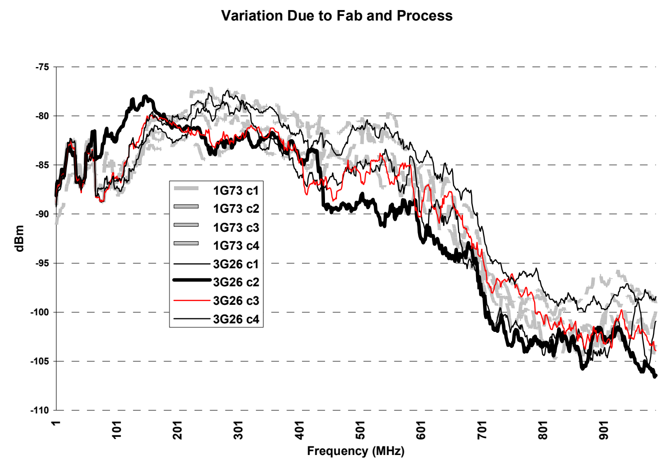

Figure 8 - IC Emissions Variation Due to Fab and Process Variation

The micros with sub nanosecond internal rise times can be expected to have measurable spectra above 1 GHz. Conversely, if this internal rise time is not known, it can be estimated from the spectral output. It was determined that the scan rate needed to be appropriate to the software execution time in order to adequately capture the emissions profile. Based on this analysis, a microprocessor signature can be obtained that identifies the IC relative to the other configurations and operating parameters that can be employed. This signature is particularly useful for A to B comparisons between various implementations of the IC functionality using different die shrink factors, I/O configurations, fab sources or other process options. The effect of these variables on the RF emissions of the IC as utilized in a circuit can thus be estimated. Figure 9 compares the spectral signatures of three microprocessors.

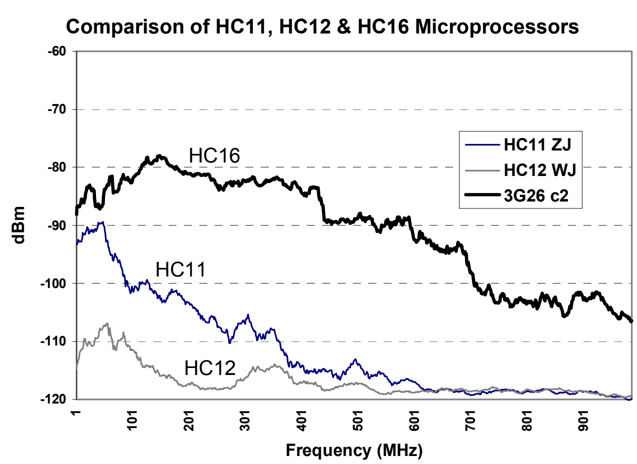

Figure 9 - Comparison of a Family of Microprocessors

We confirmed that the measurements made using the 1 GHz Fischer TEM cell were repeatable and consistent within ± 0.5 dB. The use of the 1 GHz or (2 GHz) TEM cell in conjunction with a near field scanner should allow a correlation of measured radiated emission levels with an identified internal IC structure. The 20 dB of emissions variation that we observed due to process variation, and the repeatability of the TEM cell measurement procedure, make a convincing case for the use of this technique to provide a signature analysis of a microprocessor and the use of this signature as a benchmark when the effects of process variations are being evaluated

V. Evaluation of the Effects of IC Internal Structure, Software Level, Environmental Temperature and IC Packaging on Emissions

The authors presented another paper titled *Measuring the Radiated Emissions from a Family of Microprocessors Using a 1-GHz TEM Cell, Slattery, Muccioli, North (1999)*. In this work, we investigated the relationship between the internal structure of an IC, software level differences, the IC environmental temperature and the RF emissions generated by the IC. Figure 10 is a comparison of filtered spectrums for the same IC functionality implemented in multi chip module (MCM) and discrete versions.

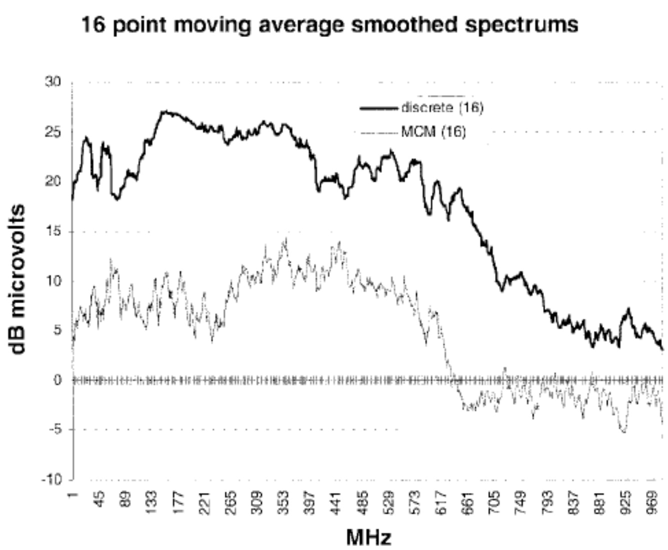

Figure 10 - Comparison of Emissions from MCM and Discrete IC Implementations

Figure 11 shows that the TEM cell measurement procedure can indicate variation in emissions levels due solely to software variation. The dark line shows a measure of the emissions for an earlier version of software. The lighter dashed line shows a more recent software level. One observes that the emissions have increased from 50 to 550 MHz. The third line shows the emissions due to software from a different product that uses the same processor. All of these emissions measurements were taken using the same processor, but programmed with three different sets of code.

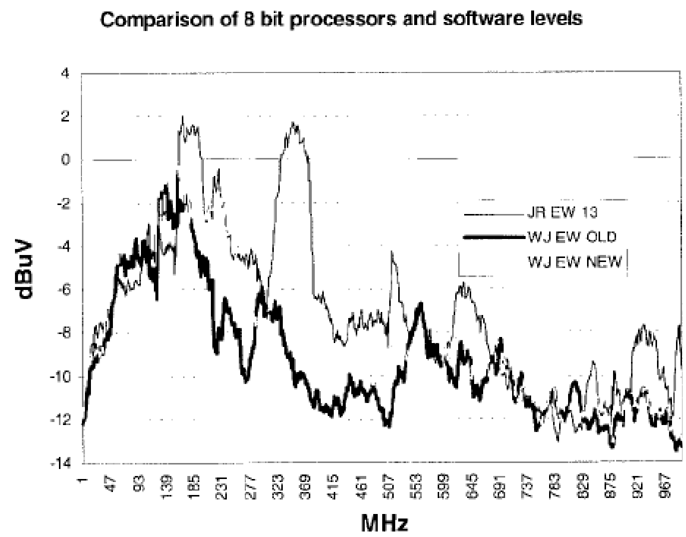

Figure 11 - Spectral Differences due to Software Level

Figure 12 compares spectral emissions as a function of temperature, ambient at 25 degrees C, cold at -40 degrees C and hot at 100 degrees C.

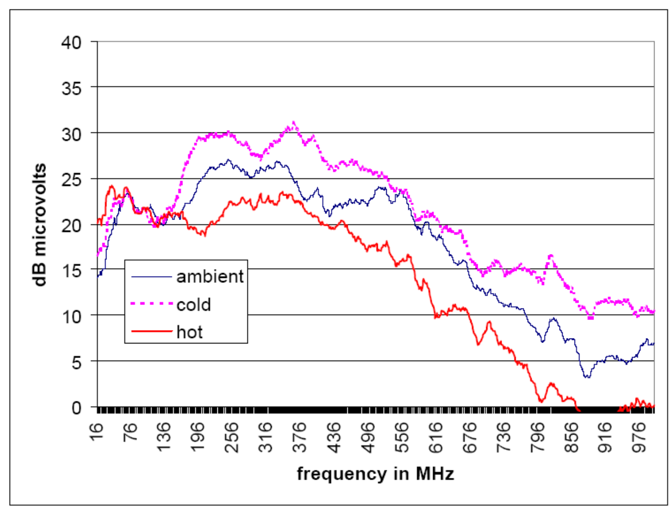

Figure 12 - Spectral Emissions as a Function of the IC Environmental Temperature

This work is greatly expanded on in later studies using the surface scan method to characterize the RF current distribution over an IC die or package. This study supported the ability of the IC TEM cell method to deliver fast and repeatable measurements and expanded on work to provide analytical modeling of the IC. This IC modeling was further developed in the paper *Modeling the Radiated Emissions from Microprocessors and other VLSI Devices, Slattery, Muccioli, North (2000).*

The effect of IC packaging on IC emissions was examined in the paper *Constructing the Lagrangian of VLSI Devices from Near Field Measurements of the Electric and Magnetic Fields, Slattery, Muccioli, North (2000)*. The aim of the authors was to study the effect of different package topologies on a given VLSI die, running identical code in each implementation. Each of the devices described has been measured at the module level for conducted emissions at the I/O connector. A comparison is given in Figure 13.

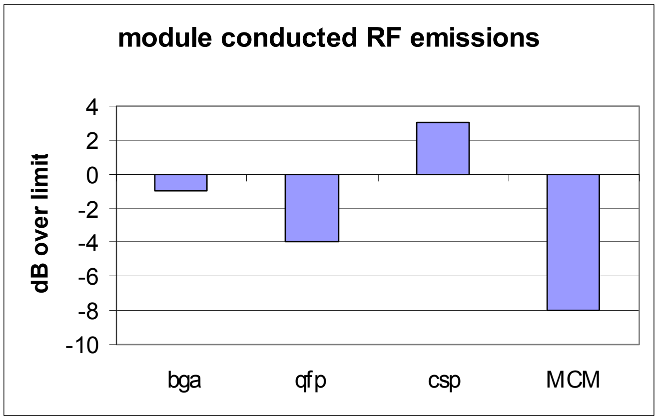

Figure 13 – Relative Emissions Comparison of Four IC Package Implementations

VI. CORRELATION BETWEEN IC AND FAR FIELD MEASUREMENTS

Near field scanning is utilized to acquire sufficient data to allow a representation of an unintentional radiating source, such as an IC, by an equivalent surface current distribution in the paper, *Using Near-Field Scanning to Predict Radiated Fields, Shi, Cracraft, Zhang, DuBroff, Slattery, Yamaguchi (2004).* This equivalent current source is then utilized in full wave computer modeling to predict the radiated EMI such a source would produce. This parallels similar studies using the TEM cell to estimate the surface current distribution of an IC.

The paper, *Electromagnetic Emissions: IC-Level versus System-Level, Deutschmann, Winkler, Ostermann, Lamedschwandner (2004)* attempts to bridge the gap between IC level measurements and system level measurements. The authors state that in a previous work they had concluded that TEM cell IC measurement results can be used to gain a general prediction of the overall emissions of the electronic system. The authors identify that, in addition to the measured IC emissions, more information is needed in order to predict with confidence the EMC behavior of an IC as it is actually utilized in a complete system. As a step in this direction, the authors discuss the use of a modified single wire model to approximate typical PCB traces. Measurement of current on these traces can then be used to estimate the far field radiation of the PCB and of the electronic system of which it is a part. The basic approach is to calculate the spectral content of an IC's switching current as measured into a specified load. The determination of this switching current can be carried out by measurements or simulations. It is recognized that this simple approximation using a one layer PCB is not representative of more complex systems.

In the paper, *Predicting TEM Cell Measurements from Near Field Scan Data, Weng, Beetner, DuBroff (2006),* the authors propose a procedure to accomplish this by modeling the near field scan data using equivalent sources. Near field measurements are made and compensated for probe characteristics then an equivalent magnetic and electric field model is generated from these compensated fields. These equivalent sources are used in an analytical formula or full wave simulation to predict measurements made using a TEM cell. Experimental verification of the method indicated close agreement between measured TEM cell data and simulations that were calculated from near field scan data. Figure 14 compares the TEM measured coupling data with that derived from simulation and from an analytical formula.

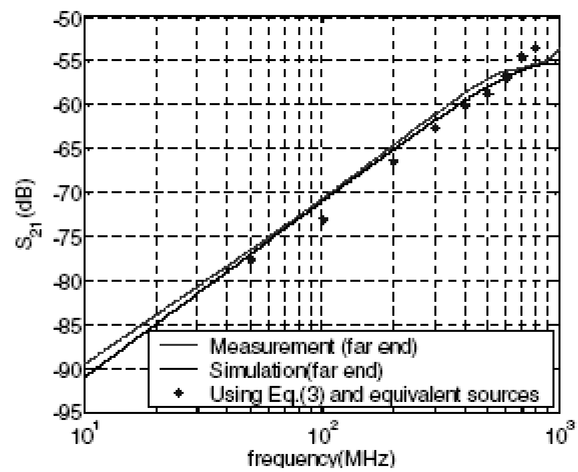

Figure 14 - Comparison of TEM Cell Measured Data with Simulation Data and Analytical Formula Calculations both Generated from Near Field Scan Data

The authors also cite previous research that showed correlation between surface scan and TEM cell measurements, but without a precise method of numerical prediction *(Near field measurements to predict the electromagnetic emission of integrated circuits, Deutschmann, Pitsch, Langer (2005)).* These studies serve to confirm a relationship between the TEM cell method of IC emissions measurement and near field scanning measurements. In some instances it may be more desirable to measure the emissions from the IC as mounted on a production PCB rather than on the standard test board required for the TEM cell measurement. In this case, surface scan data can be used to predict the TEM cell results.

VII. EXTENSION OF THE 1 GHZ TEM CELL METHOD TO SEVERAL GHZ USING A SMALL GTEM CELL

A small GTEM cell has been modified with a IC test board port and used to allow measurement to frequencies in the several GHz range. Figure 15 compares the relative impedance of the Fischer TEM cell to this small GTEM cell adapted for IC measurements. The data indicates the tendency of the TEM to go into multimoding, particularly above 1.6 GHz and the flatness of the GTEM over this frequency range.

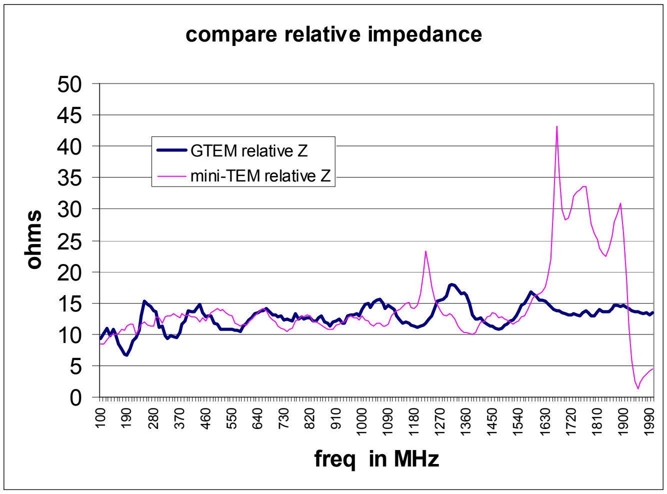

Figure 15 – Impedance Comparison of Fischer TEM Cell with GTEM

Figure 16 compares electric and magnetic field measurements between the TEM and GTEM cells and Figure 17 compares data measured on the two cells. Figure 18 shows electric and magnetic field data taken on the GTEM cell to 10 GHz, this indicates that the GTEM is usable far beyond the useful range of the TEM cell, extending the usefulness of the method to these higher frequencies. Figure 19 is a ¾ picture of the small GTEM cell with an IC Test Board Port.

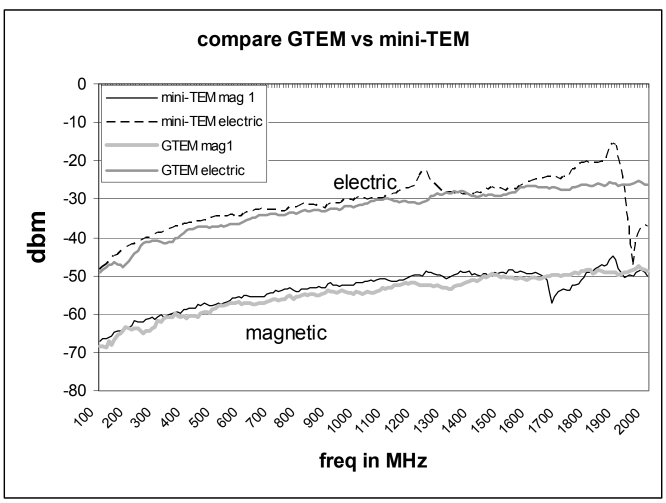

Figure 16 - Comparison of Electric and Magnetic Fields as Measured in the TEM and GTEM Cells

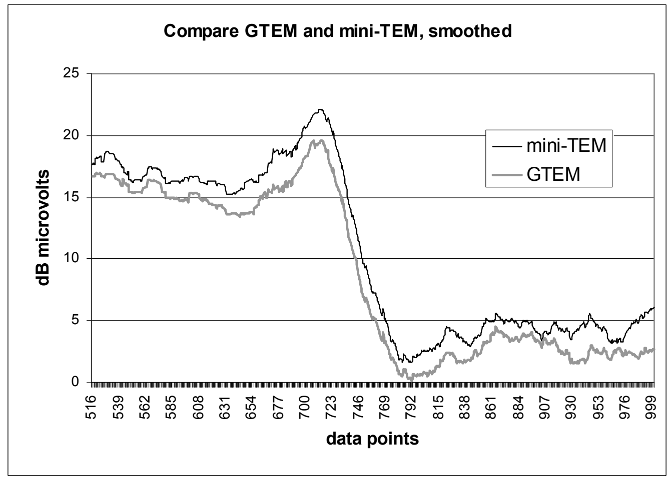

Figure 17 - Comparison of Measured IC Data on both the TEM and GTEM Cells

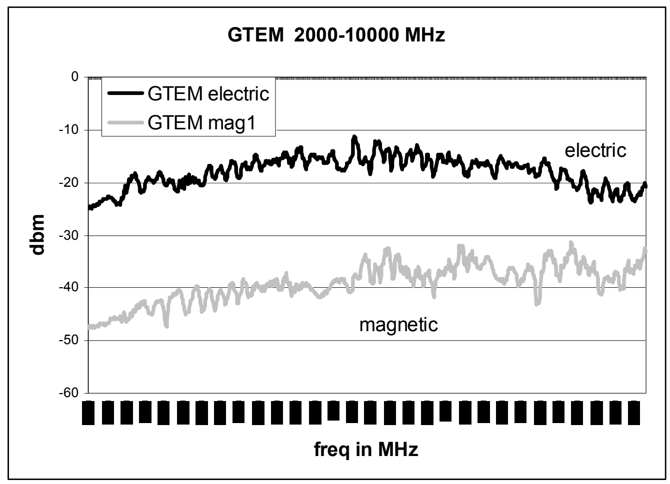

Figure 18 - Electric and Magnetic Field Measurements on the GTEM Cell to 10 GHz

Figure 19 - Small GTEM Cell with IC Test Board Port

VIII. Related IC Emissions Measurement Standards

Two standards have been developed from this research, SAE J1752-3 Measurement of Radiated Emissions from Integrated Circuits – TEM / Wideband TEM (GTEM) Cell Method, TEM Cell (150 kHz to 1 GHz), Wideband TEM Cell (150 kHz to 8 GHz) and IEC 61967-2: Integrated circuits - Measurement of electromagnetic emissions, 150 kHz to 1 GHz - Part 2: Measurement of radiated emissions, TEM Cell and wideband TEM cell method. Both SAE and IEC have also published related surface scan measurement procedures.

IX. Conclusions

We have attempted, in this paper, to trace the development of the methodology for measuring IC emissions using a TEM or GTEM cell along with the related methodology of surface scanning. There are, of course, other related research activities that we were not able to describe here, but we have been able to show the theoretical basis, numerical modeling and empirical observations that many researchers have developed over the twelve years since the first paper on the topic was presented in 1996. The repeatability and correlation between these IC emission measurement methods and other methods, including far field measurements, have been well established. Because of the many variables involved in the application of a particular IC in a module, including PCB layout, packaging and cabling, IC measurement methods will never be able to completely eliminate module level EMC measurements. However, these techniques allow the design engineer to obtain an estimation of resultant module level emissions based on IC level measurements. This estimation can be made more effective using reasonable assumptions about the effects of application specific variables on the resultant module emissions. These assumptions can then be pre validated for limiting cases to provide a reasonable range of expected results. Of particular interest for high frequency applications, this method can utilize a GTEM cell enabling emission measurements up to 10 GHz, which is beyond the current capability of other IC measurement techniques.

X. References

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[2] Model of IC Emissions into a TEM Cell, Engel, 1997 IEEE International Symposium on EMC

[3] Characterization of the RF Emissions from a Family of Microprocessors Using a 1 GHz TEM Cell, Muccioli, North, Slattery, 1998 IEEE International Symposium on EMC

[4] Measuring the Radiated Emissions from a Family of Microprocessors Using a 1-GHz TEM Cell, Slattery, Muccioli, North, 1999 IEEE International Symposium on EMC

[5] Modeling the Radiated Emissions from Microprocessors and other VLSI Devices, Slattery, Muccioli, North, 2000 IEEE International Symposium on EMC

[6] Constructing the Lagrangian of VLSI Devices from Near Field Measurements of the Electric and Magnetic Fields, Slattery, Muccioli, North, 2000 IEEE International Symposium on EMC

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[10] Near field measurements to predict the electromagnetic emission of integrated circuits, Deutschmann, Pitsch, Langer, 5th International Workshop on Electromagnetic Compatibility of Integrated Circuits, November 2005, Munich, Germany

[11] SAE J1752-3 Measurement of Radiated Emissions from Integrated Circuits – TEM / Wideband TEM (GTEM) Cell Method, TEM Cell (150 kHz to 1 GHz), Wideband TEM Cell (150 kHz to 8 GHz) Society of Automotive Engineers, 400 Commonwealth Drive, Warrendale, PA 15096-0001, USA, (412) 776-4841.

[12] IEC 61967-2: Integrated circuits - Measurement of electromagnetic emissions, 150 kHz to 1 GHz - Part 2: Measurement of radiated emissions, TEM Cell and wideband TEM cell method