Investigation of the Theoretical Basis for Using a 1 GHz TEM Cell to Evaluate the Radiated Emissions from Integrated Circuits

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Abstract - This study was initiated in order to gain a better understanding of the basis for using a 1 GHz TEM cell to evaluate the radiated emissions from integrated circuits (ICs). The authors have been involved for several years with the effort to develop procedures and standards for evaluating the EMC of ICs. One of these standards, SAE J1752/3, is being used by the IC industry to characterize high speed VLSI ICs and survey the variation of RF emissions due to changes in IC process and package parameters. This standard specifies a radiated emissions measurement system using a 1 GHz TEM cell with the IC under test on a test board that is a part of the wall above the septum of the TEM cell. In order to investigate the theoretical basis for this procedure, 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. Using a microprocessor on a test board, a comparison was made of the measured data from the 1 GHz TEM cell, the EMSCAN™ circuit board analysis system and radiated field measurements using an antenna. Methods for calibration of the TEM cell were also investigated.

I. INTRODUCTION

During the development of the IC test procedures questions as to the mechanism of coupling between the IC and the TEM cell septum have been raised. As a part of our involvement with the development of these procedures, we began investigating a model for this coupling. Our investigations led us to fabricate various loop and monopole structures and to evaluate their parameters and behavior within the 1 GHz TEM cell.

II. DEVELOPMENT OF THE MODEL

A model of a current loop located a small distance above the wall of a 1 GHz TEM cell was developed to represent the structure of an integrated circuit mounted on the standardized test board which becomes a part of the TEM cell wall. A straight forward TEM model is used, modified by the near field wave impedance of a magnetic dipole.

The current distribution in the TEM cell, for an idealized H_t distribution, is given as follows [1]:

$$I(z,t)=4\frac{V_0}{Z_{TEM}}\frac{w}{h}e^{j(\omega t-kz)} \quad (1)$$

where w is the width of the idealized region, h is the height of the IC under test above the floor, and

$$Z_{TEM}=\omega\frac{\mu_0}{k} \quad (2)$$

which is approximately 377 ohms, the free space wave impedance. The TEM mode voltage is

$$V(z,t)=V_0e^{j(\omega t-kz)} \quad (3)$$

This leads to

$$V(z,t)=I(z,t)Z_{TEM}\frac{h}{4w} \quad (4)$$

The impedance term is modified by the inclusion of the wave impedance for an elementary magnetic dipole. This brings frequency dependence back into the equation. The near-field impedance is given as

$$\eta_{near\text{-}field}=\frac{E_\varphi}{H_\theta+H_r} \quad (5)$$

in spherical coordinates. This can be calculated fairly easily for an elementary magnetic dipole, is independent of the magnetic moment and depends only on the distance from the radiator and the frequency. As an example, at 50 MHz and at a distance of 1 inch, the impedance is 7.8 ohms.

The final model for the voltage would be

$$V_{TEM}=I_0\frac{Z_{TEM}Z_{dipole}}{Z_{TEM}+Z_{dipole}}\frac{h}{4w} \quad (6)$$

I_0 is an ensemble of directed currents which can be reduced to a single equivalent directed current. For the purposes here, assume it is directed entirely along the z axis. For the model, a sinusoid of constant amplitude and constant current at all frequencies was used.

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In practice, I_0 would be a summation of trapezoidal currents. In addition, it is obvious that some restrictions must apply, since in the limit as width goes to 0, the voltage goes to infinity, and as the height goes to infinity, the voltage again goes to infinity. Therefore height and width cannot be varied independently.

Using this model, theoretical predictions of the voltage that would be impressed on the septum of the TEM cell were made and compared with the measured results for the various test boards.

III. EVALUATION OF THE MODEL

Our hypothesis was that the IC could be modeled as a resultant simple equivalent current loop. To test this hypothesis, test boards with current loops orientated both parallel and orthogonal to the TEM cell wall were assembled and evaluated for correlation with the model. The 1 GHz TEM cell that we used was developed by Fischer Custom Communications. The following test boards were constructed for this evaluation:

a. 1.5 cm square shielded loop perpendicular to the ground plane, referred to as the perpendicular loop
b. 2.9 cm wide by 0.95 cm high rectangular unshielded loop perpendicular to the ground plane, referred to as the rectangular loop
c. 1.5 cm square shielded loop parallel to the ground plane, referred to as the parallel or flat loop
d. 3 cm monopole.

The parallel loop was varied in height above the ground plane from 0.028 inch to 0.5 inch. These test boards were made from copper clad printed circuit board (solid copper sheet for the rectangular loop) with the particular antenna mounted in the center and were 4 inch square to mate to the 1 GHz TEM cell port as specified in SAE J1752/3 [2]. We used these test board antennas to investigate the variables affecting the voltage impressed on the TEM cell septum as a function of the source type and orientation. When driving the loops as a source, the loop was fed from a signal generator through a 0.5 dB 50 ohm attenuator to minimize the effects of reflections due to impedance mismatch. The 1 GHz TEM cell was set up with a 50 ohm termination at one end and a cable to the spectrum analyzer at the other end. For receiving on the loops, this setup was reversed.

A picture of the TEM cell setup and the test boards that were used is shown in Figure 1. This includes the previously described loops and monopole and a microprocessor test board. The effect on the coupling to the TEM cell septum from (or to) the various antennas due to the following variables was investigated: orientation of the loop relative to the TEM cell axis, orientation of the loop relative to the cell septum and spacing of the loop from the cell wall. The loops were evaluated both as a source and as a receptor to confirm reciprocity of the system. This comparison is given in Figure 2 for the rectangular loop and the parallel (or flat) loop. There was some slight ripple noted on the response in transmit mode but the curves are within 3 dB.

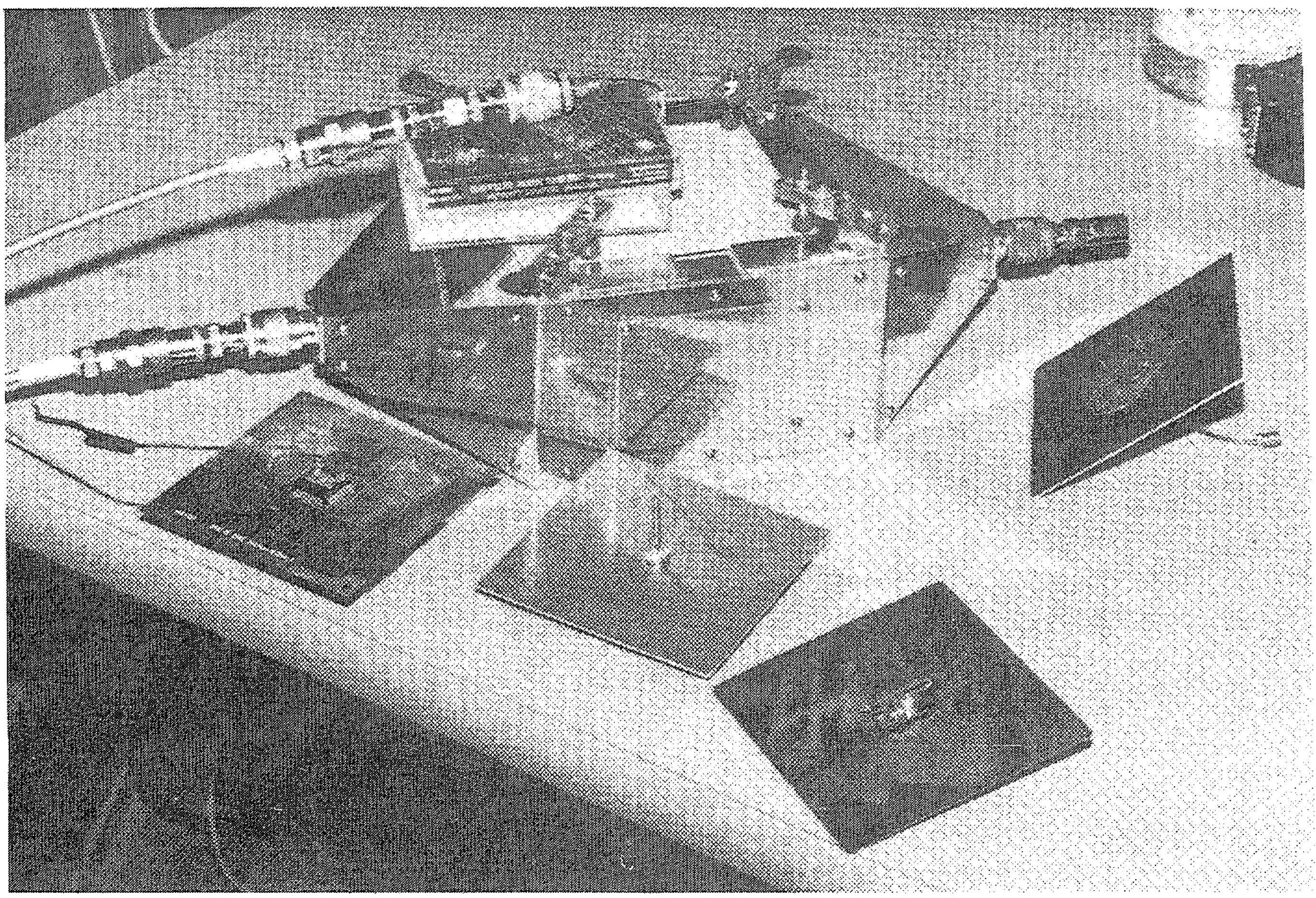

Figure 1 - System Setup: 1GHz TEM Cell and Test Boards

A comparison of the spectral output of the theoretical model and the parallel loop at a distance of 0.250 inch from the ground plane is plotted in Figure 3. The data provides agreement within 2 dB above 130 MHz and for frequencies between 10 and 130 MHz the model understates the actual results by as much as 7 dB. This is approximately the distance for minimum spectral output from this loop. The model reasonably predicts the measured output for loop to wall spacings of approximately 0.125 inch or greater. If the parallel loop is brought closer to the ground plane (TEM cell wall) than this critical distance, the error from the predictions of the model will increase. Figure 4 represents a plot of spectral output versus distance from the TEM cell wall for the parallel loop. This information is displayed in a 3-D bar chart in Figure 5 to illustrate the U-shaped response. The minimum of this family of curves is in the range of 0.125 to 0.250 inch distance from the ground plane. This suggests that another mechanism is affecting the coupling at very close spacings. Further investigation of this could lead to a more complete model.

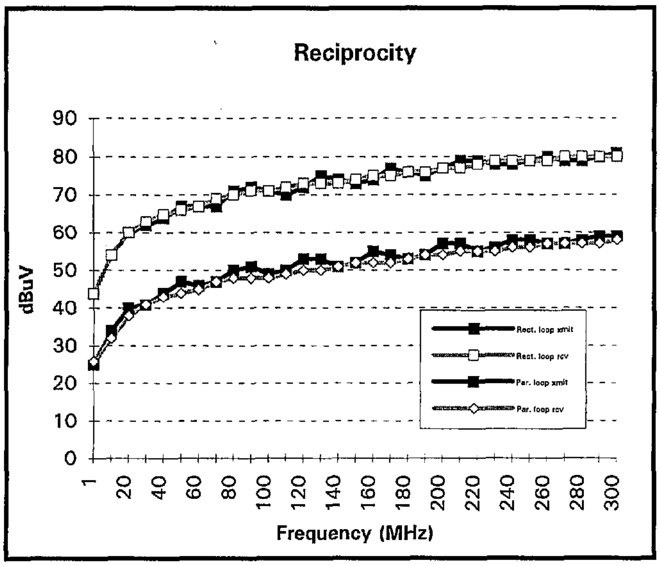

Figure 2 - Reciprocity of the System

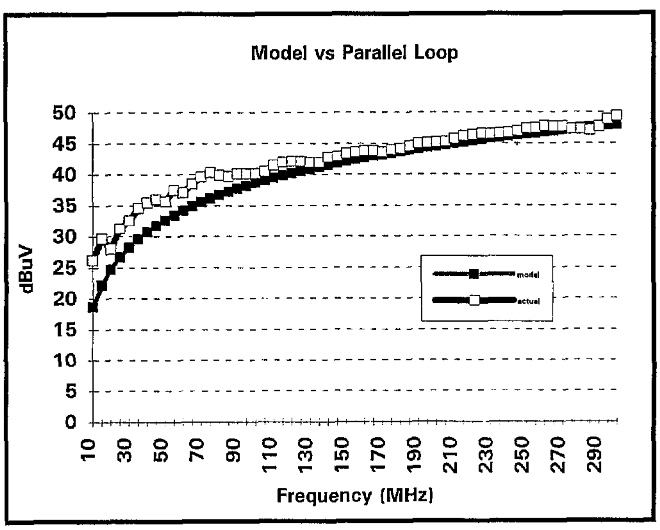

Figure 3 - Comparison of Model vs Measured for Parallel Loop

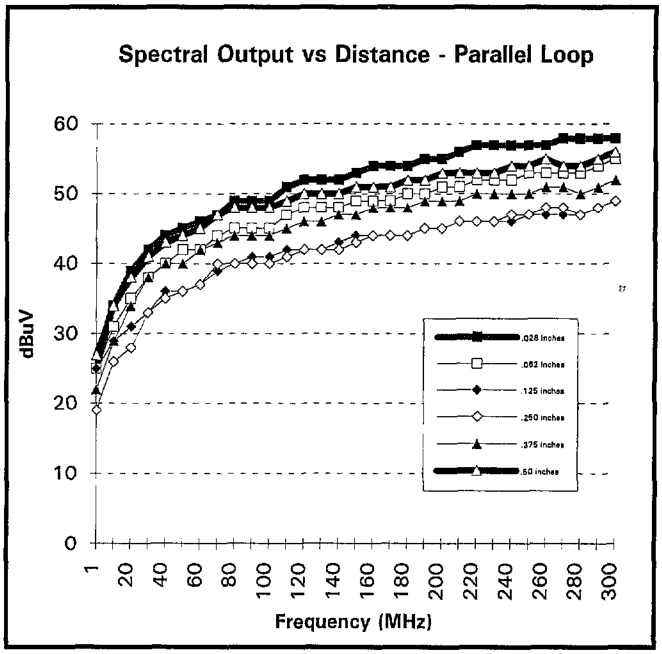

Figure 4 - Spectral Output vs Distance for the Parallel Loop

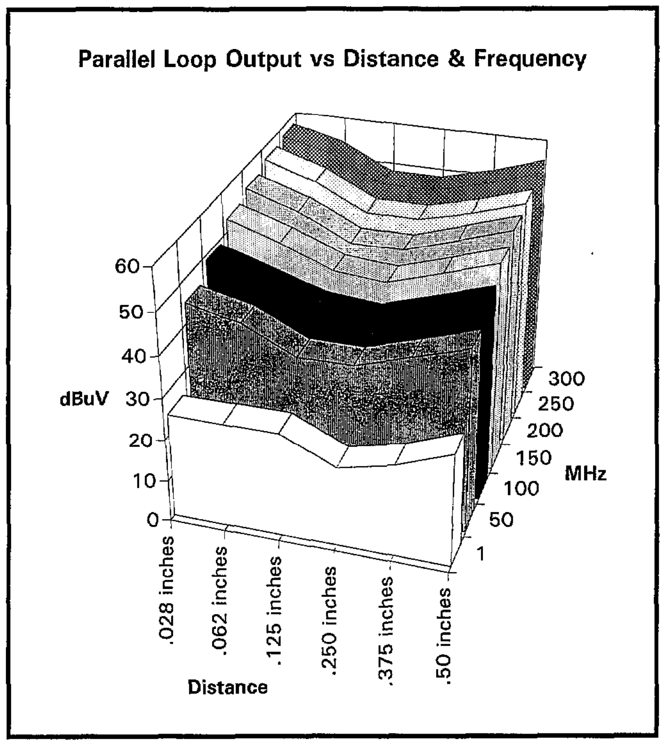

Figure 5 - U-shaped Response of the Parallel Loop

In Figure 6, comparison is made of the spectral output for the various loops and monopole. The monopole, the perpendicular loop oriented along the TEM cell axis, the rectangular loop oriented along the TEM cell axis and the parallel loop produced similar spectral output. When the rectangular loop was oriented perpendicular to the TEM cell axis the spectral output was reduced.

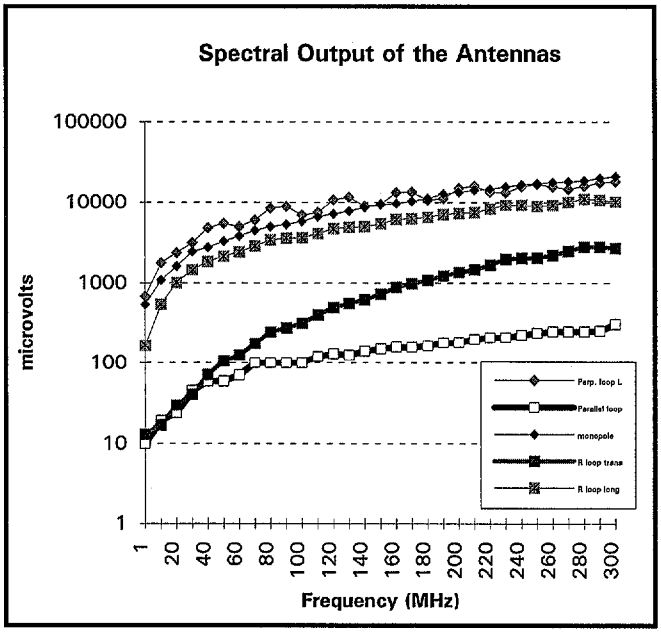

Figure 6 - Spectral Output of the Monopole and Loops

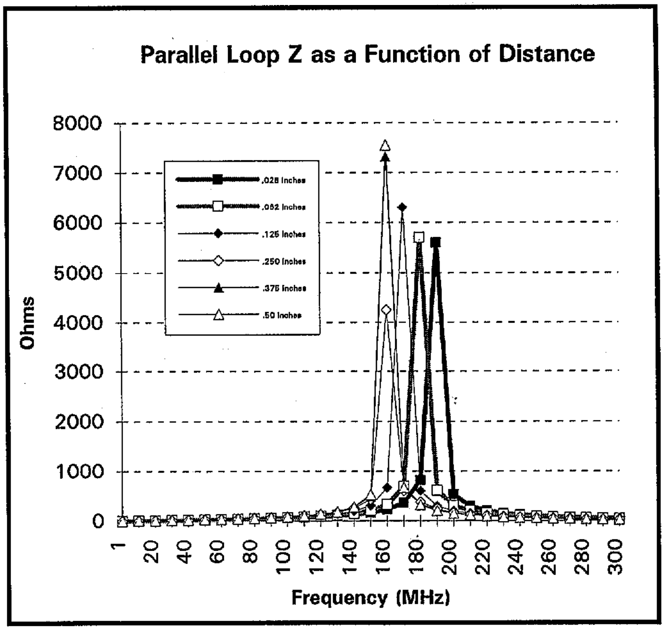

Figure 8 - Impedance of the Parallel Loop as a Function of Distance

We also investigated the impedance of the various loops and monopole and this information is presented in Figure 7. The perpendicular loop has a well defined resonance. The parallel loop has a much lower Q resonance in the same range. The monopole and the rectangular loop mirror each other with the high impedance of the monopole falling off with increasing frequency and the low impedance of the rectangular loop increasing with frequency as parasitic effects become a factor. Figure 8 indicates a frequency shift of the parallel loop resonance with spacing closer than the 0.125 to 0.250 minimum spectral output distance from the TEM cell wall. The impedance of the parallel loop decreases as it approaches the TEM cell wall.

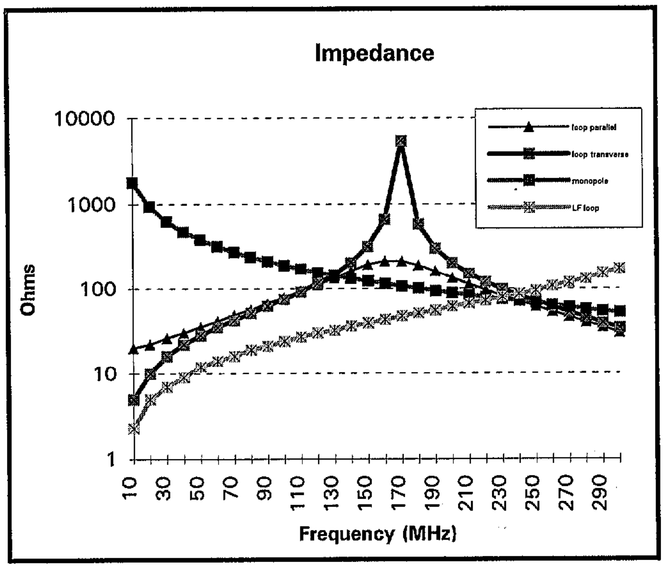

Figure 7 - Comparison of Measured Impedance for the Antennas

IV. COMPARISON TO OTHER MEASUREMENT TECHNIQUES

A standardized test board with a microprocessor was evaluated using the 1 GHz TEM cell, the EMSCAN™ system and in an absorber lined shielded room using a biconical antenna. In Figure 9, a comparison is made of the spectral response of the microprocessor test board with two orientations relative to the TEM cell axis. The difference is of the order of 14 dB and the peak at 32 MHz is 42 dBμV. The EMSCAN system consists of a table with an imbedded loop array that is interfaced with a computer and controlling software to develop a two dimensional color enhanced picture of the emission source. A plot of the spectral response of the microprocessor test board evaluated by the EMSCAN system is shown in Figure 10. The peak at 32 MHz is 42 dBμV. EMSCAN is not orientation sensitive due to the large loop array imbedded in its scan board. The TEM cell measurements and the EMSCAN evaluation show close correlation. Figure 11 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 dBμV. The vertical and horizontal scans differed by about 9 dB. For a 90° rotation of the microprocessor test board relative to the TEM cell axis, there was a 12 to 14 dB variance in spectral output. This is closer to the theoretical 20 dB difference between horizontal and vertical in free space. Overall, there was very close agreement for three completely different techniques for evaluating the radiated emissions from a source.

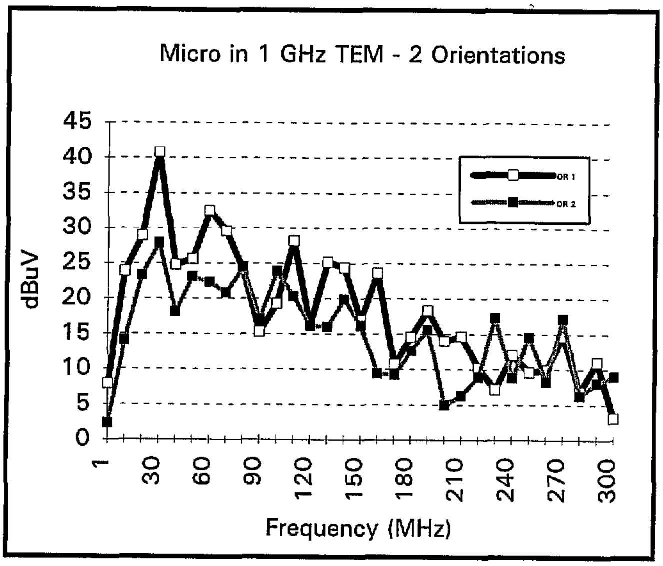

Figure 9 - Microprocessor Test Board Measured with TEM Cell

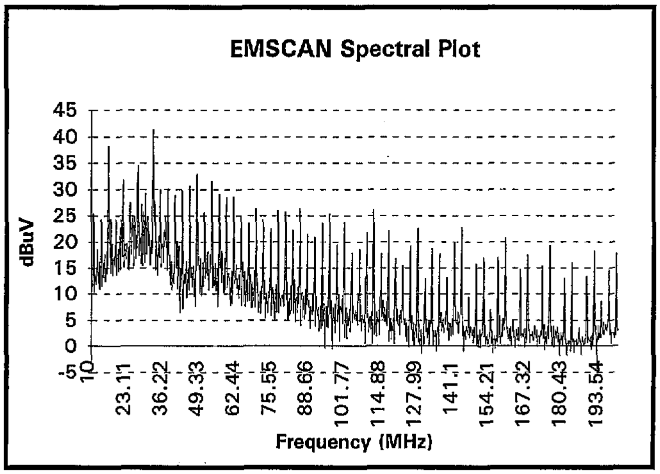

Figure 10 - EMSCAN™ Plot of Microprocessor Test Board

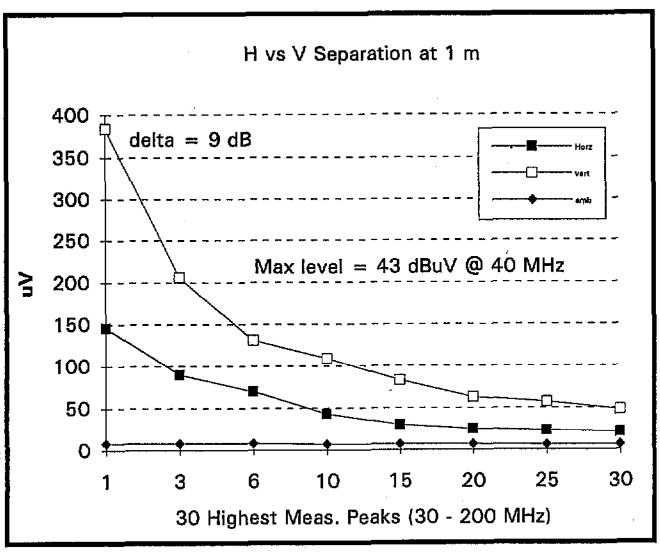

Figure 11 - Micro Test Board Measured with Biconical Antenna

CONCLUSIONS

The model was essentially confirmed by the measured data. The reciprocity and repeatability of these measurements suggest that a calibration procedure using a driven current loop similar to those that we investigated would provide a means of comparing TEM cells of different design or manufacture and calibrating a TEM cell for IC emissions measurements. Our investigations indicated that the measurements made using the 1 GHz TEM cell were repeatable and consistent. The correlation with other techniques for evaluating radiated emissions supports the use of the 1 GHz TEM cell as a valid technique for evaluating the radiated emissions from integrated circuits or other circuits small enough to be accommodated by its 4 inch square port. This supports the use of SAE J1752/3 which is being employed by industry to characterize the radiated emissions from VLSI integrated circuits and to evaluate the effect of design or process changes on these emissions.

ACKNOWLEDGMENTS

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REFERENCES

[1] Introduction to Guided Waves and Microwave Circuits, R. S. Elliott, 1993, Prentice Hall

[2] SAE J1752/3 Electromagnetic Compatibility Measurement Procedures for Integrated Circuits - Integrated Circuit Radiated Emissions Measurement Procedure, 150 kHz to 1000 MHz, TEM Cell, Society of Automotive Engineers, 400 Commonwealth Drive, Warrendale PA, 15096-0001, USA, (412) 776-4841