Quantifying Electric and Magnetic Field Coupling from Integrated Circuits with TEM Cell Measurements

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***Abstract*—One of the most widely used methods for evaluating the electromagnetic compatibility of integrated circuits (ICs) involves mounting the IC on a printed circuit board embedded in the wall of a TEM cell. TEM cell measurements are influenced by both electric and magnetic field coupling from the IC and its package. This paper describes how a TEM cell and a hybrid can be used to isolate electric field coupling from magnetic field coupling. Knowledge of the dominant field coupling mechanism can be used to troubleshoot radiated emissions problems due to ICs.**

Keywords-component; package; field coupling

I. INTRODUCTION

The twin standards SAE J1752/3 [1] and IEC 61967-2 [2] describe procedures for evaluating the electromagnetic compatibility of integrated circuits (ICs). These procedures call for the IC to be mounted on a 10-cm x 10-cm printed circuit board with the IC being evaluated on one side and the other components needed to exercise the IC on the other side. The board is mounted in the wall of a small TEM (or GTEM) cell with the IC side facing in. Voltage measured on one end of the cell is used to evaluate the performance of the IC from 150 kHz to 1 GHz.

Although the titles of these standards both contain the phrase "measurement of radiated emissions," the procedure described does not directly measure radiated emissions from the IC or its package. However, the voltage obtained from this measurement is a function of the electric and magnetic field coupling between the IC test board and the TEM cell. The electric and magnetic field coupling to the TEM cell provides an indication of how easily the IC will couple noise to other components, cables and metallic objects in other environments. IC devices that perform poorly in a TEM cell test are generally more likely to be the source of radiated emission problems in the products that use these devices.

When an IC does perform poorly, it is often helpful to know whether the coupling was primarily due to an electric or magnetic field. Electric field coupling results from voltage differences between exposed metallic parts that have a non-negligible area. Effective mitigation measures might include shielding the IC package or grounding a heatsink adjacent to the package. Magnetic field coupling is due to currents flowing in loops of non-negligible area. Coupling of this type is best reduced by making either the current or the loop area smaller. Being aware of the differences between these coupling mechanisms can help IC and IC package engineers to design better products or troubleshoot poor designs.

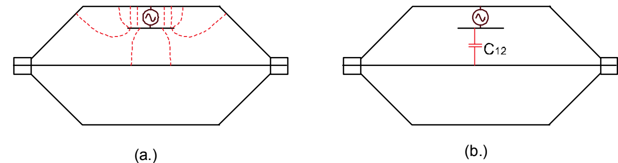

Figure 1. Electric field coupling between a metal patch and a TEM cell.

II. COUPLING MECHANISMS

A. Electric Field Coupling

Figure 1 illustrates electric field coupling in a simple TEM-cell test set-up. A voltage difference between a small patch of metal and the wall of the TEM cell produces lines of electric flux that emanate from the patch. Most of these flux lines terminate on the wall of the TEM cell; however a small portion of them terminate on the septum of the TEM cell. These flux lines produce a current in the septum that flows through the 50-ohm terminations at each end of the cell. The spectrum analyzer records the voltage induced at one end. The measured voltage is proportional to the voltage on the patch and directly related to the ability of this patch to couple electric fields to moderately distant objects. It is convenient to represent the electric field coupling between the patch and the septum as a mutual capacitance, C_{12}, as indicated in the figure. Note that if the patch is near the center of the TEM cell, the magnitude and phase of the voltage coupled to either end will be the same.

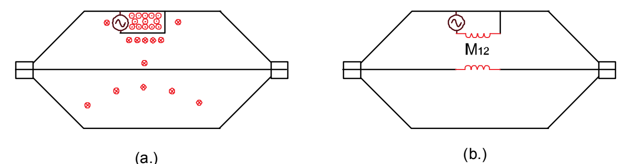

Figure 2. Magnetic field coupling between a small loop and a TEM cell.

1-4244-0294-8/06/$20.00 (c) IEEE

B. Magnetic Field Coupling

Figure 2 illustrates magnetic field coupling in a TEM cell. Current flowing in a small loop generates a magnetic field. Some of the magnetic field lines wrap around the bottom side of the septum inducing a voltage between the septum and the wall of the cell. This voltage appears across both terminations with opposite phase. The voltage measured by the spectrum analyzer is proportional to the current in the loop and related to the ability of this loop to couple magnetic fields to moderately distant objects. This coupling can be represented by a mutual inductance, M_{12}, between the source loop and the septum-cell loop as indicated in the figure.

III. Hybrid Test Set-Up

Figure 3 shows a test set-up that includes a hybrid, which generates signals that are the sum and the difference of the voltages at either end of the TEM cell. The sum of the voltages is proportional to the electric field coupling, since the electric field coupling at both terminations is in phase. Magnetic field coupling, which is 180 degrees out of phase at the two terminations, does not significantly affect the sum. The difference (A-B) output of the hybrid produces a voltage that indicates the strength of the magnetic field coupling, since the in-phase electric field coupling tends to be canceled while the out-of-phase magnetic field coupling is enhanced.

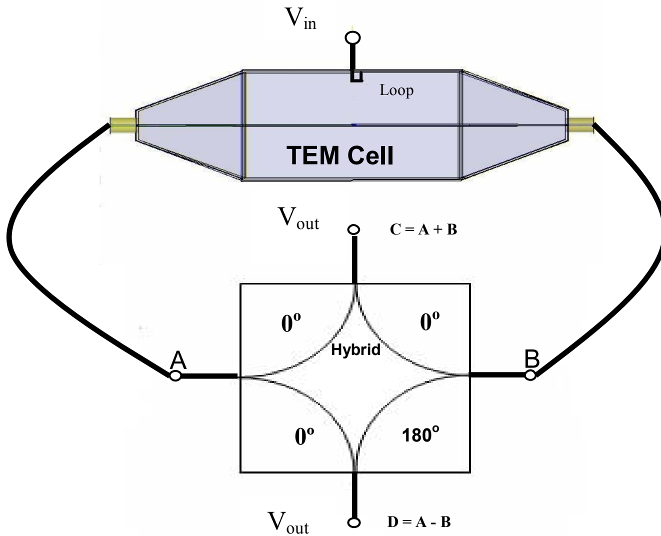

Figure 3. TEM cell with hybrid.

For the measurements presented in this paper, Port 1 of a vector network analyzer was used to drive either a small loop or a metal patch at the top of the TEM cell. Port 2 was connected to one of the outputs of the hybrid. When Port 2 was connected to the A-B output, the measured voltage transfer coefficient, S_{12}, indicated the amount of magnetic field coupling from the structure under test to the TEM cell. A similar measurement made with Port 2 connected to the A+B output of the hybrid indicated the amount of electric field coupling.

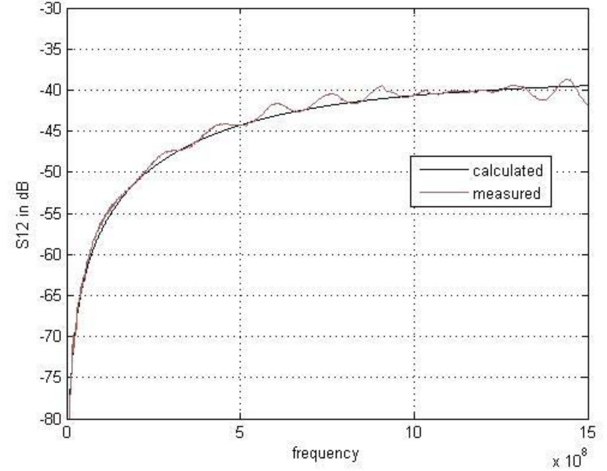

Figure 4. Coupling to TEM cell from a 2.1-cm shorted microstrip trace.

IV. Measurements

A. Shorted Microstrip Trace

A shorted microstrip trace was measured using the set-up shown in Figure 3. The structure being driven was a single microstrip trace that was 2.1 cm long and 0.2 cm wide. The measured voltage transfer coefficient, S_{12}, is plotted in Figure 4.

The magnetic field coupling between a small loop and a TEM cell can be calculated by noting that the current flowing in the septum is related to the voltage at a termination by the 50-ohm impedance of the TEM cell,

$$I = \frac{V_{in}}{50}, \tag{1}$$

This current generates a magnetic flux density,

$$B = \frac{\mu_0 I}{2(W+H)}, \tag{2}$$

near the wall of the TEM cell. The amount of flux coupled to a small loop on the wall is then approximately

$$\Phi_{21} \approx |\boldsymbol{B}|(\text{loop area}) = \frac{\mu_0 I(lh)}{2(W+H)}. \tag{3}$$

Using the equations above and correcting for the fraction of the voltage that is dropped across the 50-ohm load, we get the following formula for the voltage transfer coefficient,

$$S_{12} = S_{21} = \frac{V_{out}}{V_{in}} = \frac{\omega\Phi_{21}}{V_{in}} = \frac{\omega\mu_0 lh}{100\times(W+H)}\left[\frac{50}{50+j\omega L}\right]. \tag{4}$$

where,

L is the inductance of loop formed by the shorted microstrip trace; (In this case, L = 9.1 nH as measured with a vector impedance meter.)

l is the length of the trace;

h is the thickness of the PCB board;

W is the width of the TEM Cell;

H is the height of the TEM Cell;

Φ_{21} is the flux linking the microstrip loop to the TEM cell.

In this example, 2.5 dB was added to the result obtained using Equation (4) to correct for the loss in the hybrid. The calculated value of S_{12} versus frequency is also plotted in Figure 4. The agreement between the measured and calculated values is generally within a few dB over the entire frequency range.

The trace length was increased from 2.1 cm to 3.2 cm, which increased both the measured and calculated values by approximately,

$$20\log\frac{3.2}{2.1} = 3.7\ dB \tag{5}$$

as shown if Figure 5. The inductance of the longer trace increased to 12.4 nH, which affected the results at the higher frequencies.

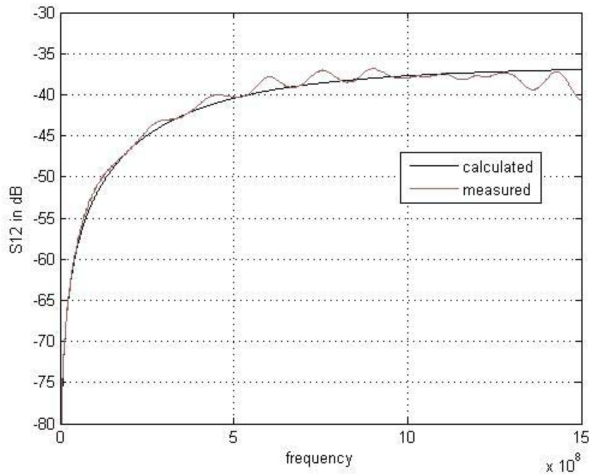

Figure 5. Coupling to TEM cell from a 3.2-cm shorted microstrip trace.

B. Square Patch and Open Microstrip Trace

Two boards that each had a square patch of copper over a ground plane were built and measured using the hybrid TEM cell set-up in Figure 3. The “reference” patch was 0.65 cm on a side. The other patch was 0.46 cm on a side (half the area of the reference patch). Measurements of the electric field coupling from these patches are shown in Figure 6. There is nearly a 6-dB difference in the two measurements indicating that the coupling is approximately proportional to the patch area.

A similar measurement was performed on boards with relatively long and narrow traces. The reference trace was 2.1 cm long and 0.2 cm wide. It had approximately the same area as the reference patch. The second trace was half as long, but had the same width. The measured electric field coupling is plotted in Figure 7. The results are similar to the results obtained for the square patch, especially below 1 GHz. This suggests the coupling is more dependent on the area of the copper patch than on the shape.

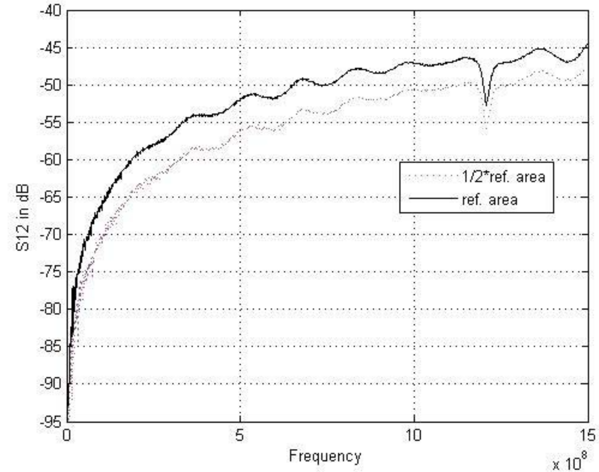

Figure 6. Electric field coupling from a square patch.

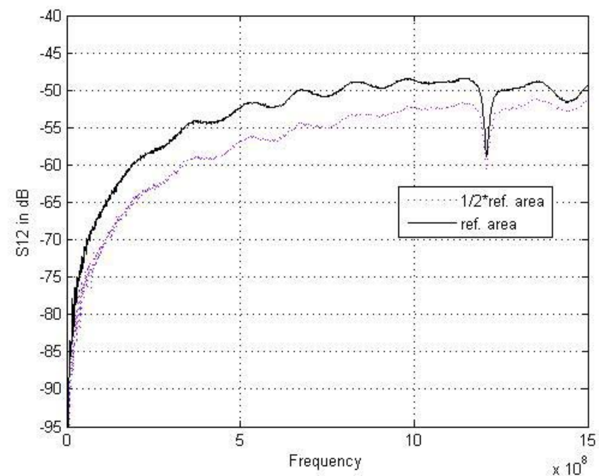

Figure 7. Electric field coupling from a long trace.

We can derive an expression for the mutual capacitance between the device under test and the TEM cell as follows.

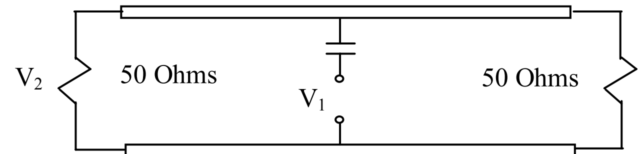

Figure 8. TEM Cell equivalent circuit for E-field coupling.

Consider the TEM cell equivalent circuit shown in Figure 8. Solving for the ratio of the input to output voltage yields,

$$\frac{V_1}{V_2} = \frac{\frac{1}{j\omega C} + 25}{25} \quad (5)$$

Expressing the voltages and currents in terms of ABCD parameters we get,

$$\begin{bmatrix} V_1 \\ I_1 \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} V_2 \\ I_2 \end{bmatrix} \quad (6)$$

or

$$V_1 = AV_2 + BI_2 = AV_2 + B\frac{V_2}{50} = V_2(A + \frac{B}{50}). \quad (7)$$

Parameters A and B can be expressed in terms of S parameters as,

$$A = \frac{(1+S_{11})(1-S_{22}) + S_{12}S_{21}}{2S_{21}} \quad (8)$$

$$B = Z_0 \frac{(1+S_{11})(1+S_{22}) - S_{12}S_{21}}{2S_{21}} \quad (9)$$

and from (7),

$$\frac{V_1}{V_2} = (A + \frac{B}{50}) = \frac{1+S_{11}}{S_{21}} = \frac{\frac{1}{j\omega C} + 25}{25} \quad (10)$$

Thus,

$$C_{12} = \frac{1}{j50\pi f(\frac{1+S_{11}}{S_{21}} - 1)}. \quad (11)$$

The equivalent mutual capacitance of the two patch and two trace configurations was calculated from the measured S_{12} using Equation (11). The results are plotted in Figure 9. The electric field coupling from each of these patches or traces can be modeled fairly well with a single capacitance up to about 1 GHz. The value of the equivalent capacitance varies less than a couple of dB in this range.

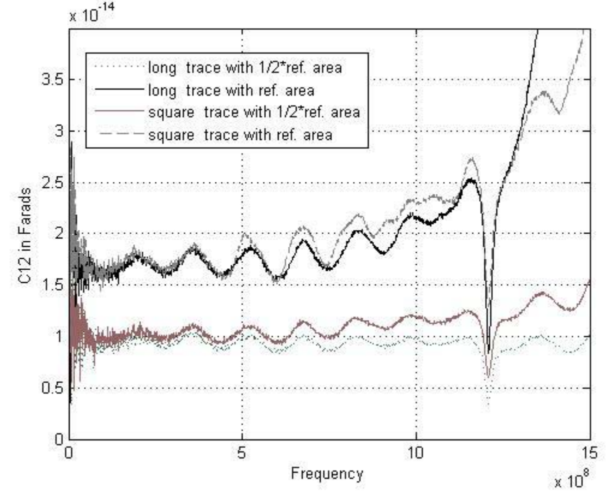

Figure 9. Equivalent mutual capacitance between measured patch or trace geometries and the TEM cell.

V. Conclusions

Measurements of shorted and open-circuit microstrip traces demonstrate that the coupling from integrated circuit devices below 1 GHz can be modeled with simple equivalent mutual inductances or mutual capacitances. By connecting both outputs of a TEM cell to a hybrid, it is possible to separate the electric field coupling from the magnetic field coupling. Information about the relative amounts of electric and magnetic field coupling can be used to determine the countermeasures that will effectively mitigate coupling from an integrated circuit and reduce radiated emissions.

References

[1] 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), Jan. 2003.

[2] IEC 61967-2:2005, "Integrated circuits – Measurement of electromagnetic emissions, 150 kHz to 1 GHz – Part 2: Measurement of radiated emissions, TEM-cell and wideband TEM-cell method", First edition, Sep. 2005