Mode Suppressed TEM Cell Design For High Frequency IC Measurements

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Abstract—**TEM cells or GTEM cells can be used to evaluate the radiated emissions of integrated circuits (ICs). The applicable frequency bandwidth of a TEM cell is limited due to the resonances of higher order modes. This paper describes how a TEM cell can be modified to extend the frequency range without changing the test topology. Several methods are proposed and implemented to suppress the higher order modes. The magnetic field coupling and electric field coupling are evaluated for the new design. The frequency bandwidth of the modified TEM cell is extended from original 1 GHz to 2. 5 GHz.**

Keywords-TEM cell; radiated emissions; higher order mode

I. INTRODUCTION

A TEM cell is a closed rectangular stripline with tapered region at each end. The standard IEC 61967-2 [1] describes procedures for evaluating the electromagnetic compatibility of integrated circuits (ICs) using a TEM cell. The IC under test is mounted in the middle of a 10-cm x 10-cm printed circuit board (PCB). The board is mounted in the wall of a TEM cell with the IC side facing into the cell. Voltage measured on one end of the cell is used to evaluate the performance of the ICs.

The measurement frequency range is limited by the TEM cell bandwidth. Transverse electromagnetic (TEM) mode wave is supported to propagate from one end of the TEM cell to the other end. Besides the TEM mode, TE modes and TM modes can also propagate in the TEM cell above their cut-off frequencies [2-5]. The frequency bandwidth of a TEM cell is limited by the resonances of higher order TE modes and TM modes.

In order to increase the bandwidth of a TEM cell which is used in IC radiation measurement, the resonances of higher order TE or TM modes should be suppressed, but the TEM mode and the shielding efficiency should not be affected. Several different methods have been introduced on suppressing higher order mode resonances in a large TEM cell [6-8]. All those methods were found effective to dampen resonances, but all of them were tested only for a large-size TEM cell with frequency range up to 1.5 GHz, and some of those methods interrupted the TEM mode or affected the shielding quality. For a TEM cell that is used to measure the radiations from ICs on a standard test board, the frequency bandwidth usually is required to be higher than 2 GHz.

A widely used standard TEM cell FCC-TEM-JM1 has a frequency bandwidth from DC to 1 GHz. In this paper, several methods are proposed and applied to a modified TEM cell, which has a similar geometry with the standard cell, trying to extend the bandwidth higher than 2 GHz without changing the cell size and test board size.

II. MODIFIED TEM CELL STRUCTURE

A. Suppressing TE Mode

Transverse electric (TE) modes are the first several modes to appear in a TEM cell with the increase of frequency [2], [9]. The corresponding resonant frequencies of those TE modes disturb the field TEM mode field distribution inside the TEM cell. The resonances of those TE modes determine the bandwidth of a TEM cell. For TEM mode, both the electric field vectors and the magnetic field vectors are perpendicular to the longitudinal direction (z direction). For TE modes, only the electric field vectors are perpendicular to the longitudinal direction and the magnetic field vectors are in the longitudinal direction. For a TEM cell working within its bandwidth, TEM mode dominates and there should be no significant magnetic field in the longitudinal direction. TE modes appear in the TEM cell when the frequency is higher than the corresponding cutoff frequencies. At the resonant frequencies of TE modes, the field distribution is disturbed and the magnetic field in the longitudinal direction is significant.

A standard TEM cell is simulated using a full wave 3-D solver HFSS [10] to investigate the effect of the TE modes. Figure 1 shows the simulation results of S parameters at two ends of the TEM cell. The S_{11} is better than 15 dB and S_{21} is better than 1 dB up to 1 GHz. There are 3 major resonant frequencies at 1.87 GHz, 2.23 GHz and 2.63 GHz respectively when frequencies are higher than 1 GHz.
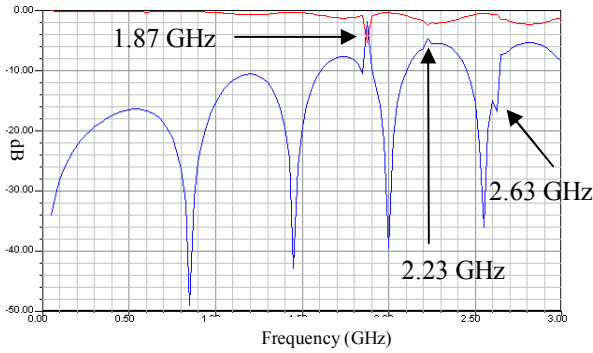
Figure 1. HFSS simulated S_{11} and S_{21} for the standard cell

A measurement of the S parameters of the standard cell using a network analyzer also shows same resonant frequencies. The magnetic field vectors at these resonant frequencies are plotted at the observation plane as shown in Figure 2. At these resonant frequencies, the TE modes (with longitudinal z-direction magnetic field) disturb the field distribution inside the TEM cell. At other frequencies where the TEM mode dominates, the magnetic field vector is within the x-y plane and there is no z-direction magnetic field vector shown in the simulation results. CST Microwave Studio [11] also output similar simulation results.
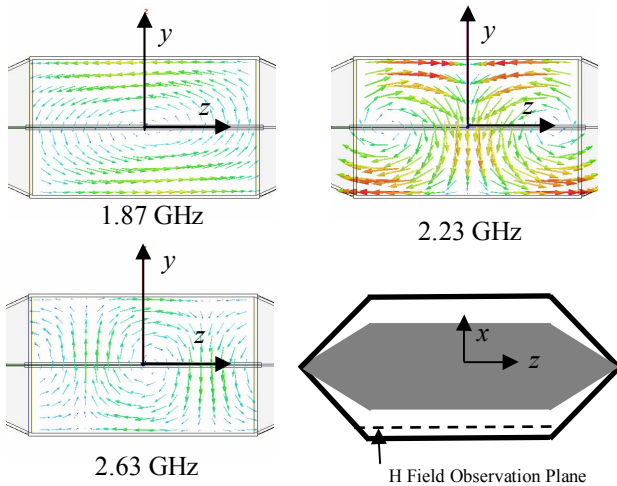

Figure 2. Longitudinal magnetic field (H_Z) at resonant frequencies.

Attempts to suppress the TE modes should involve reducing the current that flows in the x-y plane in order to minimize the longitudinal magnetic field. The modification should not change the TEM cell test topology shown in IEC Standard 61967-2 [1], i.e. keeping the cell size same as the standard cell and keep the opening size 10-cm by 10-cm for the test board. The modification should also keep the TEM mode in the cell unaffected and the shielding quality undamaged. Considering these requirements, several major modifications are performed for the corresponding TEM cell.

- Two-layer PCBs with parallel traces in longitudinal direction were used as the septum and side walls in

order to prevent current flowing in transverse direction.

- Resistors were used in the x-direction and y-direction on the septum and the walls in order to reduce the transverse current.

- The modified TEM cell is surrounded by lossy absorbing materials and an outer shielding aluminum box in order to keep the cell electrically sealed.

A parallel-trace cell is capable of suppressing generation of higher order modes [12]. With the surrounded lossy absorber and outer shielding box, the leakage from the parallel-trace cell and the interference from the outer space are minimized.

B. Structure of the Modified TEM Cell

The geometry of the modified TEM cell is same as that of the standard cell with an additional aluminum box in the outside as shown in Figure 3. Lossy absorbing material is inserted between the PCB walls and the external aluminum shielding box in order to absorb high-frequency energy and minimize interference.
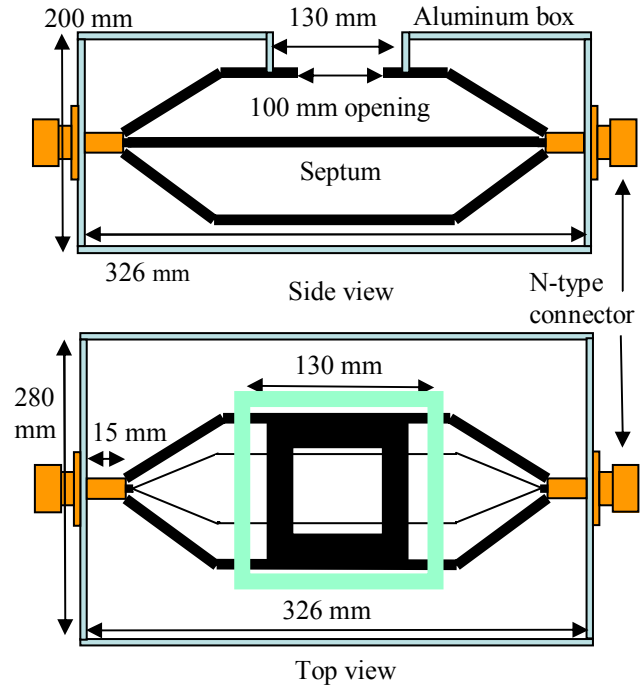

Figure 3. Geometry of the modified TEM cell.

Instead of a single metal septum as in the standard cell, a two-layer PCB septum with parallel traces on both sides is constructed as shown in the Figure 4. A 40-ohm resistor is placed at each gap connecting the adjacent traces. The resistors and gaps prevent current from flowing in x direction. Several surface mount 2-ohm resistors are mounted inside the holes in the septum connecting traces at each layer. With this structure, the current in the longitudinal direction is not affected, but the current in the transverse plane is suppressed, therefore the longitudinal magnetic field can be reduced.
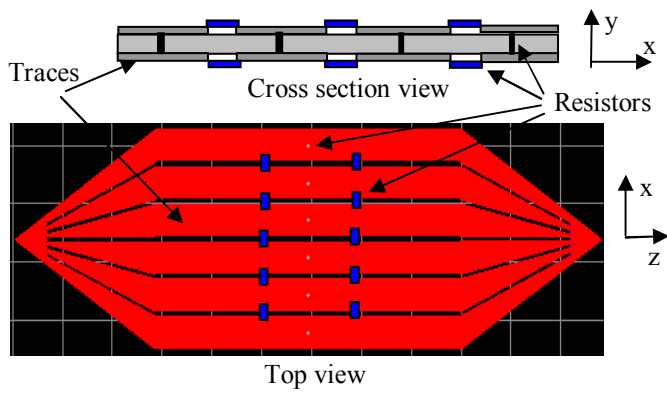
Figure 4. PCB septum of the modified TEM cell.

The walls of the modified TEM cell are also made from PCBs with parallel traces on both sides as shown in Figure 5. There are many vias connecting the traces on both sides in order to maintain a good connection between traces on opposite layers. Copper foil is used to wrap the edges of the boards to short the traces at both layers. A number of 40-ohm resistors are connected between the parallel traces in order to reduce the transverse currents.
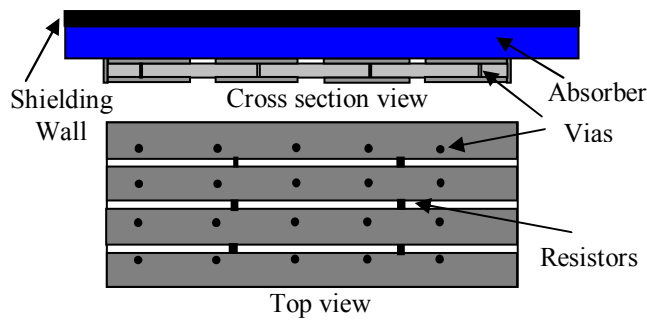

Figure 5. PCB walls of the modified TEM cell.

The PCBs are connected using copper tapes and soldered together as shown in Figure 6. In the adjusting process, a time domain reflectometer (TDR) is used to ensure the impedance of the TEM cell at both ports are as close to 50 ohm as possible.
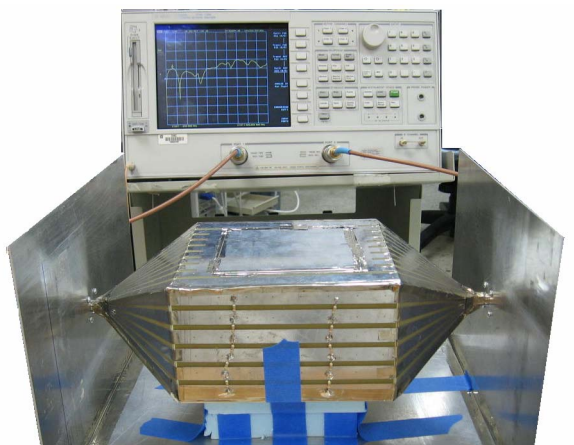

Figure 6. Measurement of S parameter for the modified TEM cell.

C. Simulation Result of the Modified TEM Cell

The effect of modified TEM cell on suppressing TE modes is evaluated by using the full wave simulation tool CST Microwave Studio. Figure 7 shows the S parameter results for the modified TEM cell model with only the parallel traces on the walls. For the cell with only the parallel traces, the TE modes still disturb the TEM field in the cell at resonant frequencies of 1.8 GHz, 2.2 GHz and 2.6 GHz.

The model is revised with 20-Ohm resistors mounted between adjacent traces and the results are shown in Figure 8. The resonances are moderated with the introduction of the resistors, which indicates that the TE modes are suppressed effectively.

The outer shielding box and the lossy absorber are included in a further revised model and the results are shown in Figure 9. The TE modes are suppressed more, with the resonances shown in the S parameters curves removed completely.
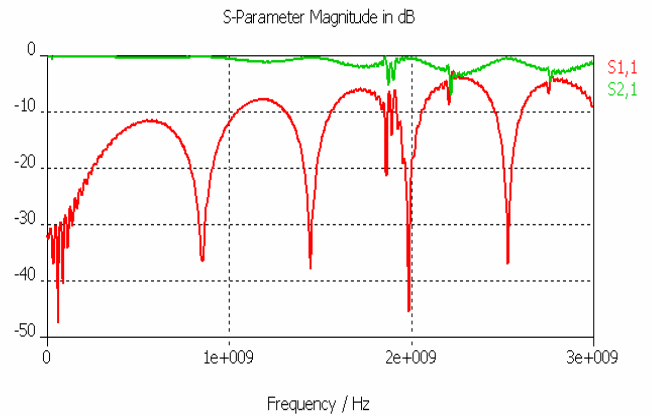

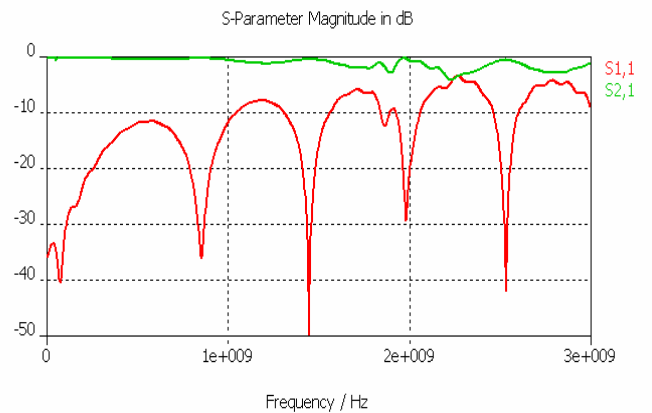Figure 7. Simulated S parameters for open parallel-trace cell.

Figure 8. Simulated S parameters for open parallel-trace cell with resistors between adjacent traces
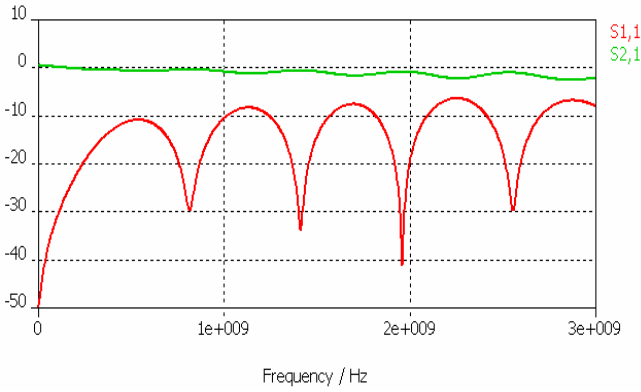
Figure 9. Simulated S parameters for modified TEM cell with outer shielding box and lossy absorber

III. MEASUREMENT OF MODIFIED TEM CELL

A. Transfer and Reflection Coefficient Measurement

The modified TEM cell is evaluated by comparing its properties to the standard cell, which has the same geometry. The S_{21} comparison results measured at the two ports using a network analyzer are shown in Figure 10. The losses for the modified TEM cell remain below 3 dB up to 3 GHz. The loss function is smooth and it does not show the resonances as the standard cell shows at frequencies below 3 GHz. This indicates that the suppression of higher order modes is functioning.
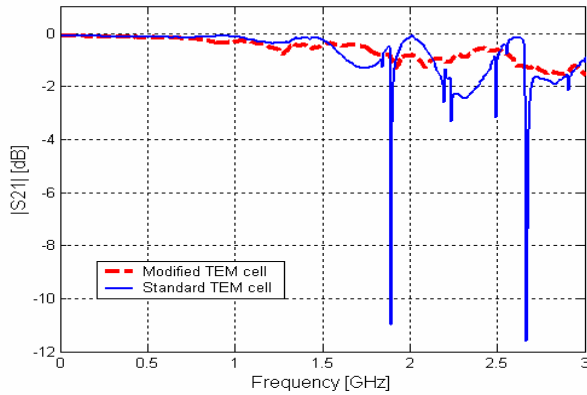

Figure 10. S_{21} data, comparing the modified TEM cell to the standard cell

The measured reflection coefficient S_{22} and S_{11} are shown in Figure 11 and Figure 12 respectively. Figure 11 indicates that the match of the modified cell, looking into port 2, is better than 20 dB up to 3 GHz. It is significantly better matched than the standard cell, which is worse than 20 dB above 1 GHz. Figure 12 shows that the match looking into port 1 is not as good as port 2, but remains better than 20 dB up to 2 GHz and better than 16 dB up to 3 GHz.
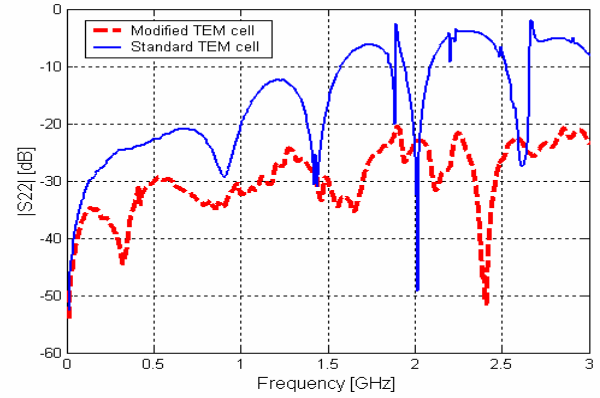

Figure 11. S_{22} data, comparing the modified TEM cell to the standard cell
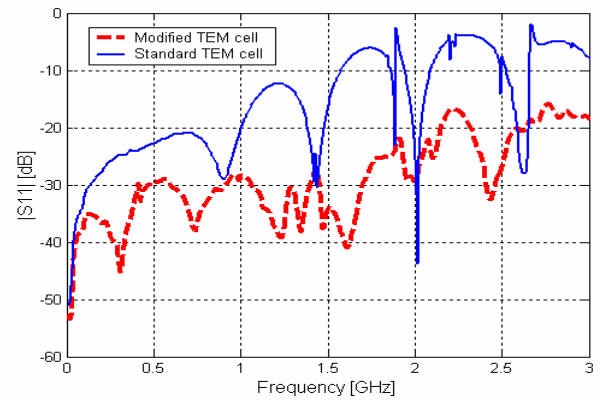

Figure 12. S_{11} data, comparing the modified TEM cell to the standard cell

B. Magnetic Field Coupling Measurement

A semi-circle loop probe is used to measure the magnetic field near the wall inside the TEM cell as shown in Figure 13. If the loop plane is positioned perpendicular to the longitudinal direction, then H_Z is picked up by the probe; if the loop plane is parallel to the longitudinal direction, then the coupling to the loop probe due to H_X is measured.
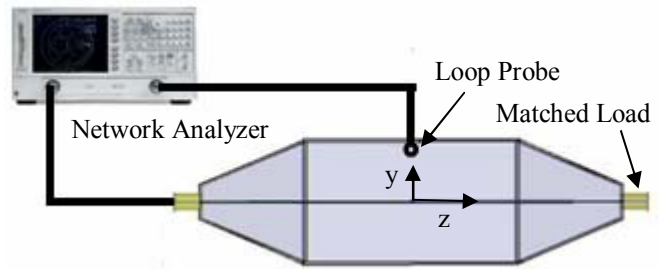

Figure 13. Magnetic field measurment setup.

The measured coupling due to H_Z and H_X are shown in Figure 14 and Figure 15 respectively. Figure 14 shows that the H_Z component in the modified TEM cell is well suppressed comparing to that in the standard cell. Note that the standard

cell shows a larger H_Z component below 1 GHz. This is most likely due to the loop orientation. If the loop is slightly misaligned then it will capture a small portion of the H_X field.

The main field component is quite similar in both cells up to 2 GHz. The difference below 0.5 GHz is most likely a result of a mechanical instability in the loop used. This is observed during testing. The main TEM mode component H_X is not expected to reduce above a certain frequency. However, the measurement for the modified cell shows a drop of the H_X component above 2.5 GHz. The loop size used is very small (about 3 mm in diameter) so that a self resonance of the loop is not likely to happen. If this is the case, then the main H-field component is reduced above that frequency. Despite the unexpected drop of main magnetic field component, the measurement data indicate a useful frequency range of the cell up to 2.5 GHz for the modified TEM cell.

The ratios of the H_Z (due to TE mode) to H_X (due to TEM mode) for the modified TEM cell and the standard cell are shown in Figure 16. This figure indicates that the modified TEM cell is able to suppress the H_Z component by more than 10 dB up to 2.5 GHz. The bandwidth of the standard cell is limited by the resonance with a strong H_Z at 1.1 GHz.
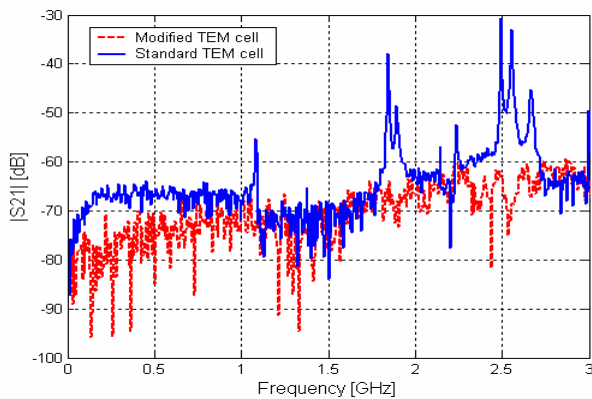

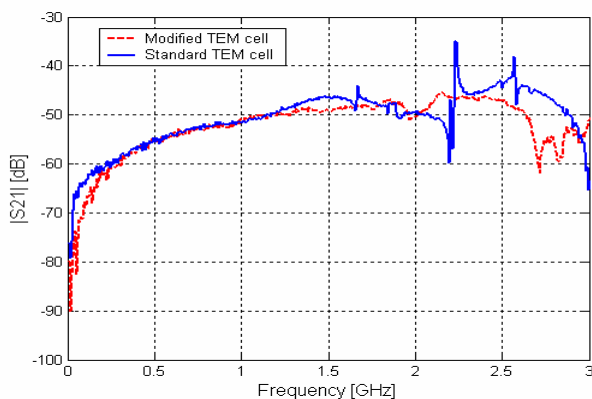Figure 14. Coupling of magnetic field component H_Z to a small semi-circle loop probe

Figure 15. Coupling of main magnetic field component H_X to a small semi-circle loop probe
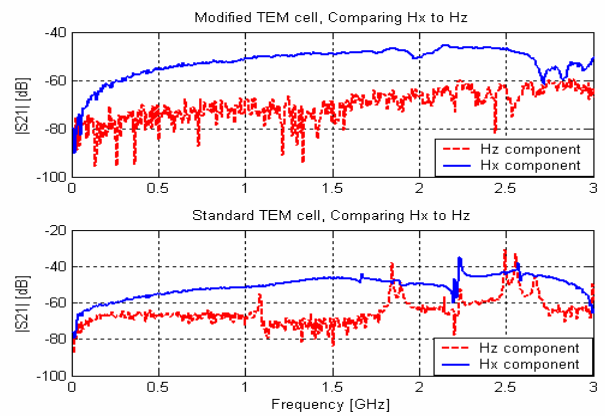

Figure 16. Ratio of H_Z to H_X (main component)

C. Electric Field Coupling Measurement

The electric field coupling in the modified TEM cell is investigated using a 10-cm x 10-cm test board [13]. At the center of the board there is a 50-ohm microstrip trace which is about 4 cm long and 1.5 mm wide. The trace is positioned perpendicular to the longitudinal direction of the TEM cell and one end of the trace is matched with a 50-ohm load. The transfer coefficient from one port of the TEM cell to the unloaded trace end is measured. The S_{21} results for both the modified TEM cell and the standard cell are shown in Figure 17. The magnetic field of the main TEM mode is in the transverse direction and it can not be coupled to the trace which is also in the transverse plane. Thus the main coupling mechanism in this measurement is the electric field. However, if present, the H_Z field will also couple to the trace. As shown in Figure 17, both cells deliver similar results below 1 GHz. At frequencies higher than 1 GHz, the non-suppressed TE mode resonances of the standard cell start to be significant on the total coupling due to the H_Z field. For the modified TEM cell, the electric field coupling is not affected significantly by those resonances up to 2.5 GHz.
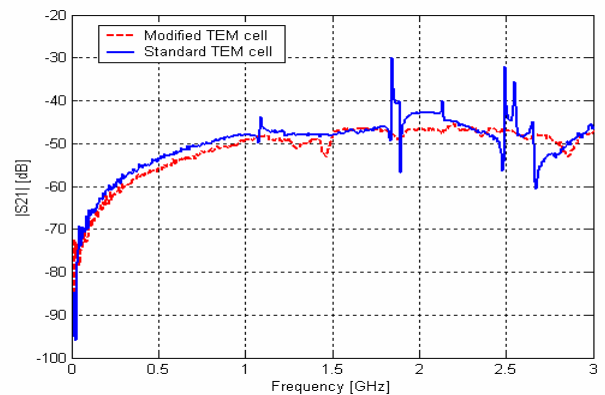

Figure 17. Electric field coupling for a terminated trace on a test board

IV. Conclusions

Undesired high order TE mode resonances limit the bandwidth of a TEM cell. A parallel-trace cell with resistors connecting the traces and lossy absorbers wrapping around the cell is proposed to suppress the TE mode. Both the measurement and the full wave simulation results demonstrate that the modified design is effective at suppressing the longitudinal magnetic field and the TE modes. The measurement results show that the modified TEM cell has similar transfer functions in both the magnetic field coupling and electric field coupling at frequencies up to 1 GHz, comparing to the original TEM cell. The frequency bandwidth of the modified TEM cell is extended from original 1 GHz to 2.5 GHz with the H_Z component suppressed by at least 10 dB. The modified TEM cell can be used to measure the radiation from ICs at frequency up to 2.5 GHz.

References

[1] 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.

[2] D. A. Hill, "Bandwidth limitations of TEM cells due to resonances," J. Microwave Power, vol.18(2), pp. 181-195, 1983.

[3] M. Koch, C. Groh, H. Garbe, "Exact Determination of Resonant Frequencies in TEM Cells," 13th International Zurich Symposium and Technical Exhibition on EMC, Zurich, Switzerland, Proceedings, pp 653-658, 1999.

[4] Ch. Groh, H. Garbe, M. Koch , "Higher order mode behavior in loaded and unloaded TEM cells," IEEE International Symposium on Electromagnetic Compatibility proceedings, vol. 1, pp. 225-230 Aug. 1999.

[5] C. Groh, P. Karst, M. Koch, H. Garbe, "TEM waveguides for EMC measurements," IEEE Transactions on Electromagnetic Compatibility, vol. 41, No. 4, pp. 440-445, Nov. 1999.

[6] D. A. Hill, J. A. Walsh, "Resonance suppresion in a TEM cell," J. Microwave Power, vol.18(4), pp. 325-330, 1983.

[7] M. L. Crawford, J. L. Workman, C. L. Thomas, "Expanding the bandwidth of TEM cells for EMC measurments," IEEE Transaction on EMC, vol. 20, No. 3, pp. 368-375, August 1978.

[8] R. Lorch, G Monich, "Mode suppression in TEM cells," IEEE Electromagnetic Compatibility Symposium Proceedings, pp. 40-42, Santa Clara, CA, 1996

[9] P. F. Wilson, M. T. Ma, "Simple approximate expressions for higher order mode cutoff and resonant frequencies in TEM cells," IEEE Transaction on EMC. Vol. 28, No. 3, pp. 125-130. 1986.

[10] Ansoft Corporation, "HFSS 10.0 User's Guide", July, 2005.

[11] CST Computer Simulation Technology, CST Microwave Studio 5.1.

[12] K. Ishihara, M. Tokuda, " Development of paralle wired cell," IEICE Technical Report, EMCJ98-104-116, 1998.

[13] V. Kasturi, S. Deng, T. Hubing, D. Beetner, "Quantifying electric and magnetic field coupling from integrated circuits with TEM cell measurements," IEEE International Symposium on Electromagnetic Compatibility, vol. 2, pp. 422 – 425, August 2006.