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An Experimental Investigation of Higher Order Mode Suppression in TEM Cells

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***Abstract*—Transverse electromagnetic (TEM) cells can be used to evaluate the electric and magnetic fields coupling from integrated circuits (ICs). The propagation and reflection of higher order modes in the cells limits the bandwidth of TEM cells. This paper investigates several methods for suppressing higher order modes in TEM cells in order to extend the applicable frequency range without changing the test topology. Numerical models and measurements of a modified TEM cell demonstrate how higher order mode suppression techniques can extend the useful frequency range of a TEM cell for IC measurements from 1 to 2.5 GHz.**

***Index Terms*—Higher order mode, resonant frequency, slotted septum, transverse electromagnetic (TEM) cell.**

I. Introduction

A transverse electromagnetic (TEM) cell is a closed rectangular coaxial transmission line with tapered regions at each end. The TEM cell is designed to propagate a single TEM mode at all measurement frequencies within the bandwidth. The standard IEC 61967-2 [1] describes procedures for evaluating the radiated emissions and electromagnetic immunity of integrated circuits (ICs) using a TEM cell up to 1 GHz. These procedures require the IC to be mounted on a 10 cm × 10 cm printed circuit board with the IC on one side and other components needed to exercise the IC on the other side. The radiated emissions test for ICs used in wireless devices usually requires the measurement frequency range to be higher than 1 GHz, the bandwidth of a typical TEM cell described in the IEC standard. At frequencies above the bandwidth of the cell, higher order mode starts to propagate in the cell and the tapered sections cause reflections of higher order modes. Thus, at frequencies higher than the bandwidth, the cell forms a resonator for higher order modes due to the reflections. The reflected higher order modes disturb the TEM mode field and make it difficult to obtain useful information from TEM cell measurements [2]–[7].

In order to increase the bandwidth of TEM cells used for IC measurements, the resonances of higher order transverse electric (TE) and transverse magnetic (TM) modes must be suppressed without affecting TEM mode propagation or the shielding properties of the cell. Several methods have been introduced to suppress higher order modes in TEM cells and these methods were shown to dampen resonances effectively [8]–[10].

A widely used standard TEM cell FCC-TEM-JM1 has a frequency bandwidth up to 1 GHz. In this paper, several methods are proposed and applied to build a modified TEM cell with a similar geometry as the standard cell. The objective of the modifications is to increase the bandwidth to at least 2 GHz without changing the cell size or the test board size. The proposed methods of suppressing higher order modes are evaluated using full-wave simulations and verified by measurements of the modified cell.

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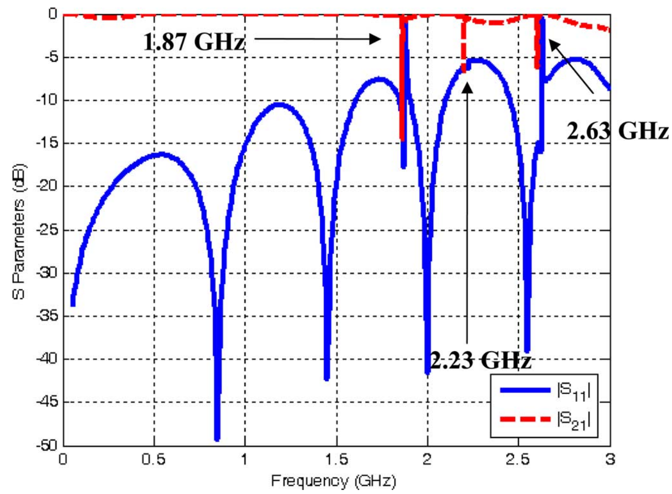


Fig. 1. S parameters for the standard TEM cell calculated using full-wave simulation.

II. Modified TEM Cell

A. Higher Order Mode-Suppressing Methods

TE modes are the first several higher order modes to appear in a TEM cell as the frequency increases above the useful measurement range of the cell [2]. TE modes first appear at frequencies above their respective cutoff frequencies. Since the cell terminations are not matched for higher order mode propagation, the cell becomes a resonant cavity and the energy in a particular TE mode is highest at frequencies corresponding to the cavity resonances.

At the resonant frequencies corresponding to TE modes, the magnetic field in the longitudinal direction is relatively high, and the TEM mode field distribution is significantly disturbed. TE mode resonant frequencies can be estimated using analytical methods [11].

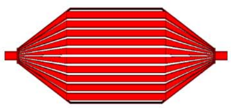
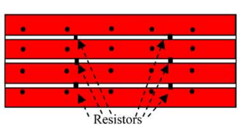
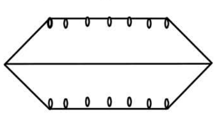
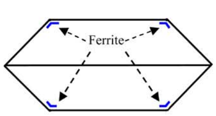
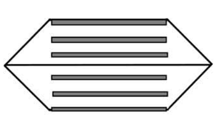
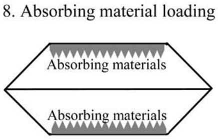
A standard IC TEM cell was modeled using a full-wave 3-D solver [12] to determine the resonant frequencies due to TE modes. Fig. 1 shows the S parameters calculated with ports 1 and 2 defined at two ends of the TEM cell. At 1.87, 2.23, and 2.63 GHz, the longitudinal magnetic field vectors inside the cell are much more significant than those at other frequencies indicating that these frequencies correspond to TE mode resonances.

One method to suppress the TE modes is to reduce the current that flows in the transverse plane in order to suppress the longitudinal magnetic field. The modification should not change the TEM cell test topology shown in the IEC Standard 61967-2, i.e., the cell size should remain the same as the standard cell and the test board opening should still be 10 cm × by 10 cm. The modification should also allow the TEM mode in the cell to propagate normally and the shielding of the cell should not be compromised. With these requirements in mind, several methods for suppressing higher order modes are proposed, as described in Table I.

B. Structure of the Modified TEM Cell

An experimental modified TEM cell was constructed implementing methods 1 through 4 in Table I. The modified TEM cell has an aluminum box around the outer side, as shown in Fig. 2. Lossy absorbing materials fill the space between the outer box and the slotted walls. With the absorber and outer shielding box, the leakage from the parallel-trace cell is minimized, and interference from outside the box is suppressed. For this structure, the current in the longitudinal direction

TABLE I
DIFFERENT METHODS FOR SUPPRESSING TE MODES IN TEM CELLS

1. Slotted walls 	PCBs with parallel traces in the longitudinal direction are used to line the outer walls in order to prevent current from flowing in the transverse direction. Currents flowing in longitudinal direction are not affected. This is similar to the parallel-wire concept described in [13].
2. Slotted septum 	Slots are cut in the septum in order to form parallel traces in the longitudinal direction and suppress any currents flowing in the transverse direction.
3. Two-layer septum with resistors 	The septum is constructed using two-layer printed circuit boards with a dielectric layer in the middle. Resistors of total 2 ohms are placed between the layers of the septum for each strip in order to achieve a 45-degree phase angle between the capacitance formed by the two layers and the connecting resistors at the resonances occurred at around 1 GHz. Thus for each septum strip, two 1-ohm resistors are used. Currents flowing in the vertical direction are attenuated by these resistors.
4. Resistors between slotted traces 	Tow 80-ohm resistors are placed in parallel between each slot connecting the adjacent traces for both the septum and the outer walls. The resistors are mounted evenly across the slots and the total resistance from edge to edge on each board is around 200 ohms (5 slots on each board). Currents flowing in the transverse plane are attenuated by these resistors.
5. Magnetic loops near the walls 	Resonant magnetic loops are placed in the corners near the floor of the cell with the magnetic dipole moment parallel to the longitudinal direction in order to cancel out some of the magnetic field in the longitudinal direction [5].
6. Ferrite tiles in the corners 	Ferrite tiles are positioned parallel to the side walls of the cell at the corners in order to absorb energy in the magnetic field associated with higher order modes [5].
7. Long narrow ferrites 	Long narrow ferrite strips are positioned along the longitudinal direction on the walls, so that TEM mode is less affected than TE modes.
8. Absorbing material loading 	RF-absorbing materials are placed inside the TEM cell to dampen the cell's high-frequency higher order mode resonances [8]. The limitations of this method are a decrease in the usable testing volume as well as reduced TEM mode field.

is not affected, but the current in the transverse plane is significantly attenuated. In other words, the longitudinal magnetic field and the corresponding TE modes are suppressed.

The TEM cell walls were connected using copper tape and soldered together. During the assembling process, a time-domain reflectometer (TDR) was used to ensure that the impedance of the TEM cell at both ports was as close to 50 Ω as possible. The assembled cell without absorbing materials and shielding box is shown in Fig. 3(a). The complete cell is shown in Fig. 3(b).

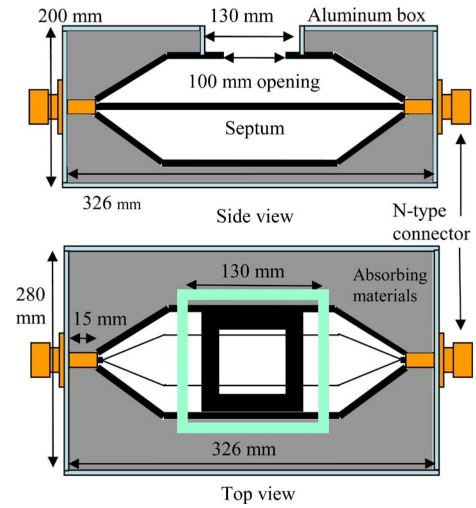
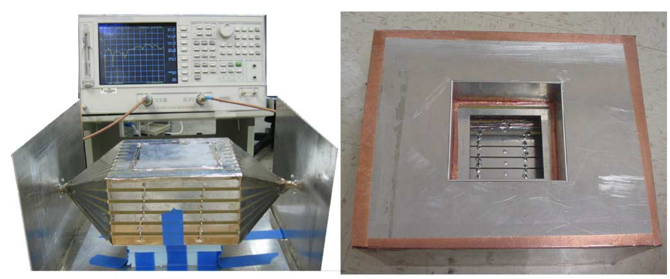


Fig. 2. Geometry of the modified TEM cell.



(a) (b)

Fig. 3. Modified TEM cell. (a) Without absorbing materials and shielding box. (b) Complete cell.

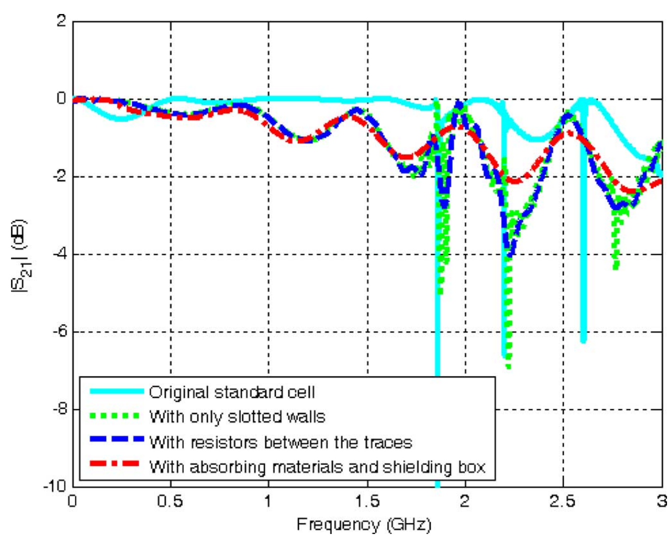


Fig. 4. Numerical simulation of different TE mode-suppressing methods.

III. EVALUATION OF THE MODIFIED TEM CELL

A. Numerical Simulation

The effect of the modifications was evaluated using a full-wave simulation tool [14]. Fig. 4 shows the calculated S_{21} for the modified TEM cell model with different TE mode-suppressing methods. The

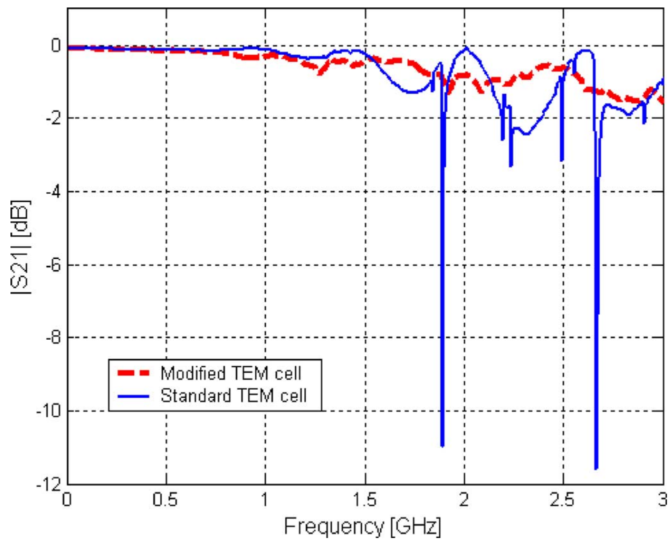


Fig. 5. $|S_{21}|$ data, comparison between the modified cell and the standard cell.

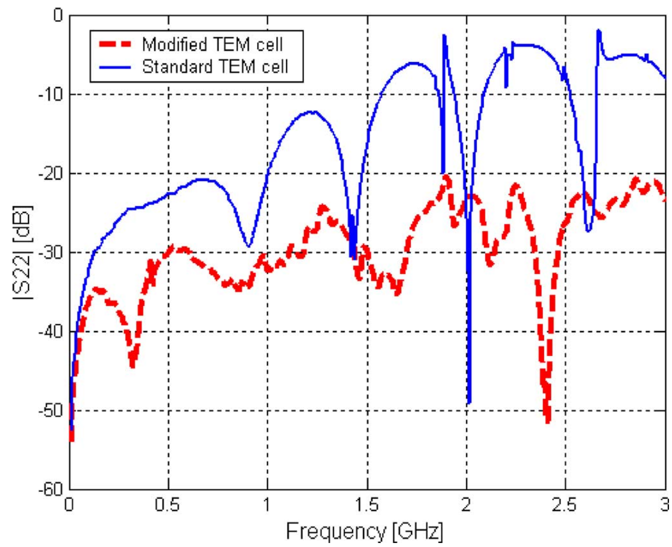


Fig. 6. $|S_{22}|$ data, comparison between the modified cell and the standard cell.

solid curves are the results of the original standard cell, with three resonant spikes at 1.8, 2.2, and 2.6 GHz. The dotted curve indicates the results obtained when the only modification was the slotted walls and the magnitude of the resonant spike at 1.8 GHz is apparently reduced. When resistors are added between the parallel traces on the walls, the magnitude of these spikes is significantly reduced, as indicated by the dashed curve. When the lossy absorbing materials and shielding box are added, those spikes are completely eliminated, as shown by the dash-dotted curve. This comparison result demonstrates that each method effectively suppressed the higher order modes resonances in the TEM cell.

B. Transfer and Reflection Coefficient Measurement

The modified TEM cell was also evaluated by comparing its measured properties to a standard cell with the same geometry. The comparison of the $|S_{21}|$ results measured at the two ports using a network analyzer is shown in Fig. 5. The loss in the modified TEM cell is less than 3 dB up to 3 GHz. The $|S_{21}|$ curve is smooth and does not exhibit any of the resonances that are obvious in the standard cell.

The measured reflection coefficient $|S_{22}|$ is shown in Fig. 6. The reflection coefficient of the modified cell, looking into port 2, is below -20 dB up to 3 GHz. It is significantly better matched than the standard cell above 1 GHz.

C. Magnetic Field Coupling Measurement

A semicircular loop probe was used to measure the magnetic field near the wall inside the TEM cell, as shown in Fig. 7. If the loop plane is positioned perpendicular to the longitudinal direction, H_Z is picked up by the probe; if the loop plane is parallel to the longitudinal direction, the coupling to the loop probe due to H_X is measured.

The ratio of the field coupling due to the H_Z component and that due to the H_X component indicates the applicable frequency bandwidth of the TEM cell. The comparison of the H_Z component and the H_X component for the modified TEM cell as well as the standard cell are shown in Fig. 8. This figure indicates that the H_Z component in the modified TEM cell is well suppressed compared to that in the standard cell. The modified TEM cell is able to suppress the H_Z component by more than 10 dB up to 2.5 GHz. Thus, by this measure, the applicable frequency bandwidth of the modified TEM cell is 2.5 GHz. The corresponding bandwidth of the standard cell is limited to 1.1 GHz due to the spike in the H_Z component. At frequencies higher than 2.5 GHz, H_X component start to decrease due to the loss of TEM mode energy. The modification suppressed the propagation of higher order modes effectively so that they cannot resonate in the cell, but the conversion

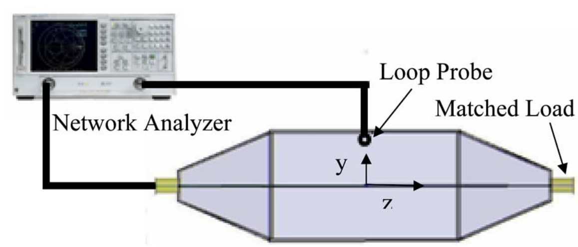


Fig. 7. Magnetic field measurement setup.

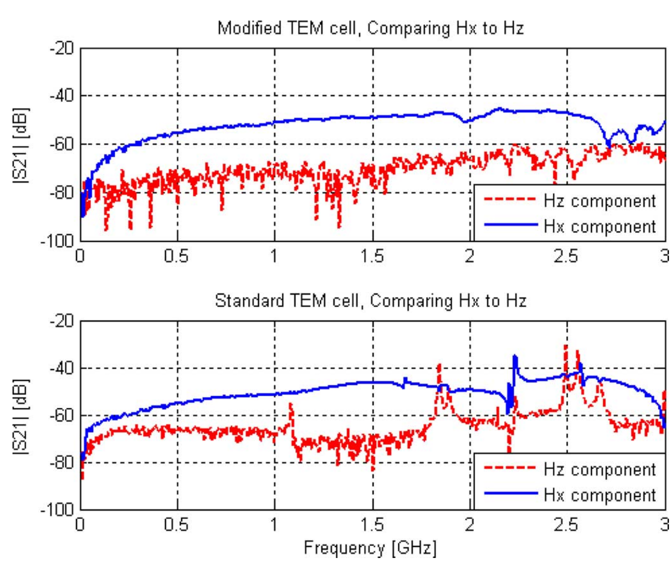


Fig. 8. Comparison of H_Z and H_X for the modified cell and the standard cell.

from TEM mode to higher order modes is not affected. Thus, the energy converted from TEM mode to higher order modes is still lost, which determines the bandwidth of the modified TEM cell.

IV. Conclusion

Undesired higher order TE mode resonances limit the bandwidth of a TEM cell. A series of methods that can be used to suppress higher order TE modes has been proposed. A modified TEM cell with slotted walls, resistors between the traces, lossy absorbing materials wrapped around the cell, and an outer shielding box was designed and assembled. Measurements and the full-wave simulations demonstrate that the modified design is effective at suppressing the longitudinal magnetic field. The bandwidth of the modified TEM cell was increased to approximately 2.5 GHz, compared to 1 GHz for the original standard cell. The modified TEM cell can be used for radiated emission and immunity testing at frequencies up to 2.5 GHz.

References

[1] *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 ed., IEC 61967-2:2005, Sep. 2005.

[2] D. A. Hill, "Bandwidth limitations of TEM cells due to resonances," *J. Microw. Power*, vol. 18, no. 2, pp. 181–195, 1983.

[3] M. Koch, C. Groh, and H. Garbe, "Exact determination of resonant frequencies in TEM cells," in *Proc. 13th Int. Zurich Symp. Tech. Exhib. EMC*, Zurich, Switzerland, 1999, pp. 653–658.

[4] C. M. Weil and L. Gruner, "Higher order mode cutoff in rectangular striplines," *IEEE Trans. Microw. Theory Tech.*, vol. MTT-32, no. 6, pp. 638–641, Jun. 1984.

[5] C. Groh, H. Garbe, and M. Koch, "Higher order mode behavior in loaded and unloaded TEM cells," in *Proc. 1999 IEEE Int. Symp. Electromagn. Compat.*, Aug., vol. 1, pp. 225–230.

[6] C. Groh, J. P. Karst, M. Koch, and H. Garbe, "TEM waveguides for EMC measurements," *IEEE Trans. Electromagn. Compat.*, vol. 41, no. 4, pp. 440–445, Nov. 1999.

[7] D. Hansen and D. Ristau, "Characteristics of the EUROTEM family," in *Proc. 1999 Int. Symp. Electromagn. Compat.*, Tokyo, Japan, pp. 86–89.

[8] D. A. Hill and J. A. Walsh, "Resonance suppression in a TEM cell," *J. Microw. Power*, vol. 18, no. 4, pp. 325–330, 1983.

[9] M. L. Crawford, J. L. Workman, and C. L. Thomas, "Expanding the bandwidth of TEM cells for EMC measurements," *IEEE Trans. Electromagn. Compat.*, vol. EMC-20, no. 3, pp. 368–375, Aug. 1978.

[10] R. Lorch and G Monich, "Mode suppression in TEM cells," in *Proc. 1996 IEEE Int. Symp. Electromagn. Compat.*, Santa Clara, CA, Aug., pp. 40–42.

[11] P. F. Wilson and M. T. Ma, "Simple approximate expressions for higher order mode cutoff and resonant frequencies in TEM cells," *IEEE Trans. Electromagn. Compat.*, vol. EMC-28, no. 3, pp. 125–130, Aug. 1986.

[12] *HFSS 10.0 User's Guide,* Ansoft Corporation. Pittsburgh, PA, Jul. 2005.

[13] K. Ishihara and M. Tokuda, "Development of parallel wired cell," The Inst. Electron., Inf. Commun. Eng. (IEICE), Tokyo, Japan, Tech. Rep. EMCJ98-104-116, 1998.

[14] *CST Microwave Studio 5.1,* CST Computer Simulation Technology, Framingham, MA.

Using TEM Cell Measurements to Estimate the Maximum Radiation From PCBs With Cables Due to Magnetic Field Coupling

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***Abstract*—Common-mode currents can be induced on cables attached to printed circuit boards (PCBs) due to electric and magnetic field coupling. This paper describes a technique for using transverse electromagnetic (TEM) cell measurements to obtain an effective common-mode voltage (or *magnetic moment*) that quantifies the ability of traces and integrated circuits on PCBs to drive common-mode currents onto cables due to magnetic field coupling. This equivalent common-mode voltage can be used to reduce the complexity of full-wave models that calculate the radiated emissions from a system containing the board. It can also be used without full-wave modeling to provide a relative indication of the likelihood that a particular board design will have unintentional radiated emissions problems due to magnetic field coupling.**

***Index Terms*—Magnetic field coupling, mutual inductance, radiated emissions, transverse electromagnetic (TEM) cell.**

I. Introduction

Common-mode currents are often a dominant source of unintentional radiated emissions from printed circuit boards (PCBs) [1]. Both electric field (capacitive) coupling and magnetic field (inductive) coupling can contribute significantly to the common-mode currents on cables attached to PCBs [2]. Models for estimating radiated emissions due to electric field coupling have been discussed in [3]. A magnetic field coupling model was presented in [4], and equations were developed to calculate this coupling for microstrip trace geometries.

The IEC 61967-2 standard [5] describes procedures for evaluating the emissions from integrated circuits (ICs) using a transverse electromagnetic (TEM) cell. The IC is mounted on a 10-cm square PCB that is secured to the wall of a TEM cell with the IC side facing into the cell, as shown in Fig. 1. The voltage measured on one end of the cell is used to evaluate the performance of the IC and the board. Recent studies [6], [7] have shown that the electric and magnetic field coupling from the IC can be isolated by measuring the output at both ends of the TEM cell and adding or subtracting the output voltages using a hybrid coupler. Electric field coupling measurements can be used to determine an "electric moment," which is a number that can be used to quantify the ability of the board to drive common-mode currents on attached cables due to electric field coupling [8]. This paper demonstrates how magnetic field coupling measurements made with a TEM cell can be used to determine a *magnetic moment* that can be used to quantify the ability of the board to drive common-mode current on attached cables due to magnetic field coupling.

II. Mutual Inductance in a TEM Cell

To illustrate how magnetic field coupling occurs between circuits on a PCB and a TEM cell, consider the microstrip trace geometry

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