Do-it-Yourself Fabrication of an Open TEM Cell for EMC Pre-compliance

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Abstract—**The Transverse Electro-Magnetic (TEM) cell is popular among EMI/EMC community ever since its invention. Its versatility in radiated susceptibility tests as well as in measuring radiated emissions from a product is well known and is widely used for in-house, pre-compliance tests. In fact, it has been used for sophisticated calibration purposes such as that of D-dot sensors. A cost effective fabrication method for an open TEM cell is presented in this paper. The proposed method uses double-sided Printed Circuit Board (PCB) sheets, instead of copper or iron sheet metal, resulting in the reduction of cost and weight of the cell. A laboratory prototype has been developed without using any specialized facility. Standard formulae are used to design the cell dimensions. Important parameters are measured and verified with the designed values. It is evident that a low cost, lightweight and efficient (low VSWR) TEM cell can be constructed using PCB for EMC pre-compliance purposes.**

I. INTRODUCTION

Transverse ElectroMagnetic (TEM) cell or Crawford cell (named after its inventor) is used to generate accurate electromagnetic waves over a wide frequency range: DC (0 Hz) to several MHz. EM waves generated in the cell propagate in transverse mode and have the same characteristics as a plane wave [1]. It can be used to calibrate E-field broadband probes for testing radiated E-field immunity as well as for measuring radiated emission from a product with a spectrum analyzer/EMI receiver. TEM cell generates a consistent electromagnetic field for testing small RF devices such as wireless pagers, GPS receivers, portable phones, etc. An external test signal applied through the input port of the TEM cell generates a consistent and predictable (plane wave) test field inside the TEM cell. A TEM cell schematic is shown in Fig. 1. The radiation field emanating from a device (under test) located in the cell can also be detected through the port using an EMI receiver. In such a case, the signal generator port will be connected to an EMI receiver or a spectrum analyzer. The Equipment Under Test (EUT) is placed on the bottom ground plane (and not on the septum) as in Open Area Test Site (OATS) and in accordance with the shielded enclosure conditions.

TEM cells are used in final compliance certification tests. There are many EMC standards (e.g., IEC 61000-4-3), which require a TEM cell for radiated susceptibility and radiated emission tests. Integrated Circuits (IC), Micro Electro-Mechanical Systems (MEMS) devices and PCBs can also be tested according to the standard SAE J1752-3 [2], [3]. TEM cells can deliver an equivalent OATS performance inside the comforts of a lab with minimum OATS errors. It obviates the requirement of an expensive shielded anechoic chamber to perform radiated EMI tests. The only disadvantage of a TEM cell is that when the operating frequency increases, it's size decreases imposing a constraint on the size of the EUT. In such a situation, however, a variant of TEM cell, known as GTEM (Gigahertz TEM) cell, may be used [4].

Fundamentally, a TEM cell is a modified stripline construction. A stripline consists of two parallel plates between which the field is established. It is essentially a two-port network where one port is used as the input and the other as output. Input as well as output sections are tapered for impedance matching. However, in a TEM cell, one of the parallel plates is constructed to enclose the other plate so that the field remains confined within the structure. The main advantage of a TEM cell over a stripline is that in the former, the EUT is completely shielded (except a window to insert/monitor the EUT) from the external environment, thus producing results with negligible errors. It is one of the reasons why a TEM cell is qualified to perform final compliance tests. However, the engineering complexity of the window fabrication due to installation of finger strip, wire mesh and conductive fabric for monitoring purpose makes the cost of a TEM cell high. Also, its fabrication requires special skill and facility.

Several variations of the TEM cell are possible depending upon the application at hand. An open TEM cell is cost effective and also most popular. It is essentially a closed TEM cell with the sidewalls opened to avoid windows' complexity and to keep the construction simple. The disadvantage of an open TEM cell, compared to a fully closed cell is that the EUT is not completely isolated from the external electromagnetic environment. Thus, in principle, an open TEM cell ranks between a stripline and a closed TEM cell and is not acceptable for final compliance testing. However, it is an ideal choice for in-house, inexpensive yet reproducible pre-compliance tests for radiated emission and susceptibility.

The main problems with the readymade, commercially available open TEM cells are that they are relatively expensive and heavy, the latter leading to handling and portability issues. Further, the in-house construction of a conventional TEM cell would need a sheet-metal workshop and costly copper/iron sheet metal. It is important to note that the TEM cells constructed from sheet metal will, in general, incur skin-effect losses.

This article presents the design and fabrication of an inexpensive, lightweight open TEM cell made from PCB sheets. The 'do-it-yourself' approach renders a simple and 'easy-to-fabricate' open TEM cell with appreciable performance.
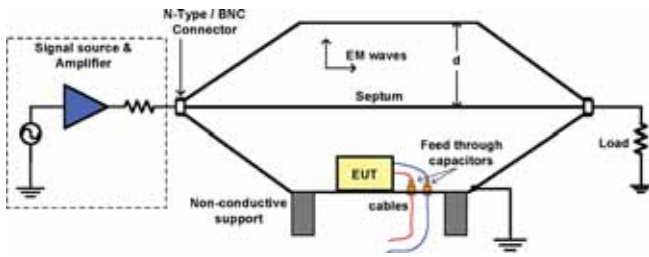
Fig. 1. A TEM cell with a signal source and the load.

II. OVERVIEW OF THE BASIC THEORY AND WORKING PRINCIPLE

The Transverse Electromagnetic (TEM) cell was first described by M. L. Crawford in 1974 [1]. The uncertainty in the generation of standard fields in TEM-cells is usually specified as ±0.5 dB. It is a co-axial transmission line with its cross section expanded over sufficient length to insert an object whose electromagnetic characteristics have to be determined. Fields generated in a TEM cell are essentially plane waves with free space wave impedance of 377 Ω. A TEM cell operates from DC (0 Hz) up to a cut-off frequency, determined by the dimensions of the cell. When a conducting object (probe, wire etc.) is placed in the field area of the cell, the characteristics of the field vary. This variation can be analytically modeled and subsequently compensated for any errors. However, for more accurate calibration, a TEM cell with larger cross section area is required [5].

Typical closed and open TEM cells are shown in Figs. 2(a) and (b). The cell consists of a section of rectangular co-axial transmission line tapered at each end to adapt to N-type connector or BNC connector. The line and the tapered transitions are designed to have a characteristic impedance of 50 Ω along the entire length, to ensure minimum VSWR. A uniform EM field is established between the plates and central conducting plane (septum) inside the cell when RF power is delivered to the cell from a signal generator connected to the input of the TEM cell. A 50 Ω resistor (termination load) is connected to the cell's output port.

The E-field (V/m) at the centre of the working volume of the TEM cell is given by [1]:

$$E = \frac{V}{d} = \frac{\sqrt{pZ_0}}{d} \tag{1}$$

where V is the rms voltage on the septum (V); d is the separation between lower/upper wall and septum (m); Z_0 is the characteristic impedance of the TEM cell (= 50 Ω) and p is the power flowing through the septum conductor of cell (W). For a practical case, (1) is modified as below [5];
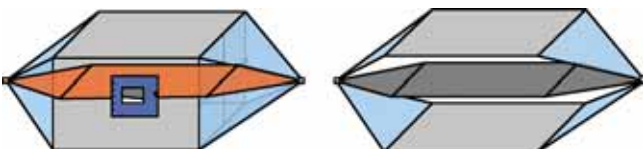
$$E = \frac{\sqrt{pZ_0}}{d} C_E \tag{2}$$

Fig. 2. Versions of TEM cell: (a) Closed TEM cell; (b) Open TEM cell.

where C_E is the correction factor for the average field strength over the volume of the EUT derived from the analysis of the field distribution over the cross section of the cell. Thus, by measuring the power flowing through the septum, the E-field can be calculated for known values of d and C_E.

The dimensions of a TEM cell are governed by its characteristic impedance and usable frequency range (first resonance frequency). The line (characteristic) impedance of the TEM cell is given by [1];

$$Z_0 = \frac{94.15}{\sqrt{\varepsilon_r}\left[\frac{w}{2d\left(1-\frac{t}{2a}\right)} + \frac{C_f}{0.0885\,\varepsilon_r}\right]} \tag{3}$$

where, ε_r is the relative dielectric constant of the medium inside the cell (1 for air); w is the width of the septum (m); t is the thickness of the septum (m); d is the distance between septum and upper wall, $2d$ is the height of the cell (m) and C_f is the fringing capacitance per unit length (0.053 pF/cm).

At low frequencies, only the fundamental or TEM mode exists in the cell with the cell operating as a 50 Ω transmission line. As the frequency increases, higher order resonant modes are induced as determined by the following equation;

$$f_{res} = \sqrt{f_{mn}^2 + \left(\frac{pc}{2l}\right)^2} \tag{4}$$

where f_{mn} is the cutoff frequency in Hz of the mode of interest; c is the wave propagation velocity (3.0×10^8 m/s); l is the resonant length of the cell (m) and m, n, and p are integers corresponding to the particular mode and the resonant length of the cell is frequency dependent (depending upon the particular mode of interest).

III. FABRICATION OF THE OPEN TEM CELL FROM PCB

The constructional dimensions of the TEM cell are mainly governed by the characteristic impedance of the cell structure seen by the source and load. For a 50 Ω source and load impedance, it is obvious to design the TEM cell with 50 Ω characteristic impedance. As mentioned before, an important limitation of the TEM cell is that its upper frequency limit is reduced, as its overall dimensions are made larger. For the presented design, an upper frequency limit of 1 GHz is chosen for the fabrication as it fulfills radiated emission frequency-band requirements. For the fabrication of the open TEM cell, by taking (3) and (4) as design guidelines, dimensions of the cell (height, width, length and tapering) are worked out and are listed in Table 1.

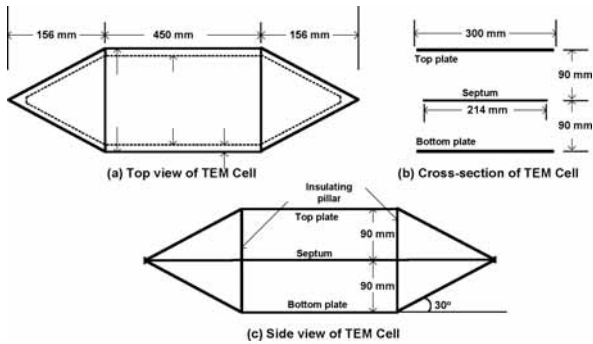| TABLE 1. DIMENSIONS OF THE TEM CELL		
View	**Name**	**Dimensions**
Top	Length (un-tapered)	450 mm
Top	Length (tapered)	156 mm × 2
Cross-section	Width (outer shield)	300 mm
Cross-section	Width (septum)	214 mm
Cross-section	Septum—outer shield	90 mm × 2
Side	Tapering angle with respect to Horizontal	≈30°

Fig. 3. Open TEM cell prototype dimensions: (a) Top view; (b) Cross-sectional view and (c) Side view.

All the dimensions are calculated manually using (2), (3) and (4). It is done intentionally to avoid the use of any software to make it as a complete 'do-it-yourself', in-house fabrication. All the major dimensions are illustrated in Figs. 3(a), (b) and (c). After computing all the necessary dimensions, the TEM cell was fabricated in the laboratory. The prototype is realized using FR4 grade, glass-epoxy double side PCB sheets. Both layers of PCB are shorted by multiple 'through holes' at every 50 mm, which is less than $\lambda/4$ for the maximum operating frequency of 1 GHz. Thus, the two sides of the PCB form an integrated sheet of thin copper, with glass-epoxy base, which is very light and easy to fabricate by using small cutting machines. All joints are done with good quality epoxy adhesive, while connectivity between conducting parts is achieved with thin copper foil and good quality bonding is achieved through continuous soldering over the entire length of joints. All joints are ensured for a DC resistance less than 10 mΩ. With the dimensions given above, the characteristic impedance (Z_0) of the prototype TEM cell as per (3) is found to be 52.4 Ω, which is very close to the ideal 50 Ω value. The working frequency range of the cell for a plane wave is beyond 1 GHz. Photograph of the prototype of a TEM cell is shown in Fig. 4.

The advantages of the PCB based open TEM cell are as follows:
(i)   It is very lightweight (approx. 2 kg as compared to the commercially available ones that are in the range of 25–30 kg). This makes it portable and handy.
(ii) Due to negligible skin-effect losses, its VSWR is better than the thick metallic (conventional) version.
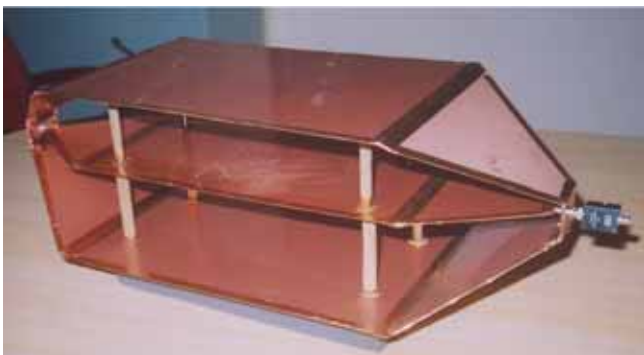(iii) Field fringing is less due to thin layer of copper cladding.

Fig. 4. Photograph of the prototype of the open TEM cell fabricated using PCB sheets in the laboratory.

(iv) Convenient to fabricate in any electronic laboratory.
However, it must be noted that the maximum power handling capacity of the PCB based cell is less as compared to a sheet metal based cell. But as far as relatively low level field generation is concerned, it is sufficient (radiated emission test applications, calibration of D-dot sensors for transient electromagnetic field etc.)

A Word About Power and Signal Cables of the EUT Placed in the TEM Cell

Coupling of electromagnetic field with the EUT's power and signal cables, running inside the TEM cell, can induce large errors. Therefore, such cables should be as short as possible. Furthermore the RF currents, which might be flowing on the outer shields of the cables, should be diverted to the ground plane of the TEM cell so that they don't couple with the power supply and other monitoring and simulating equipment associated with the EUT.

In the open TEM cell developed, a special connector topology can be used where cables are inserted via "feed through" capacitors, filtered BNC connector or even through appropriate EMI filters. The outer shields of the cables should be terminated on the ground plane, circumferentially. The "feed through" capacitors or connector can easily be mounted on the double-sided PCB of the bottom ground plate of the cell using toothed washers or even by soldering. This is illustrated in Fig. 5.

To provide some space for the protruding "feed through" capacitors and cable bending below the bottom ground plate, the cell can be elevated by a few centimeters using non-conductive support, as shown in Fig. 1. The bottom plate of the cell can be bonded to the ground using a thick, but short, grounding braid or strip.

However, it may be noted that in certain cases of radiated susceptibility tests, the governing EMC standards may require some portion of a cable to be considered as part of the EUT (e.g., in MIL-STD-461E, RS103 test, in frequency band of 200 MHz–1 GHz, first 35 cm of cables and leads interfacing with the EUT enclosure are within the 3 dB beam width of the antenna). Therefore, depending upon the testing requirements, the desired portion of a cable may be exposed to the EM radiation.
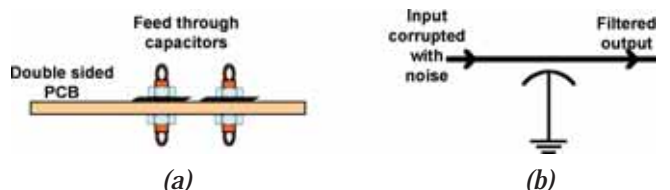

Fig. 5. (a) Fixing of feed through capacitors on the PCB of bottom ground plate (b) The corresponding electrical schematic of feed through capacitor.

IV. EFFICIENCY OF TEM CELL IN TERMS OF VSWR

Matching the TEM cell to the source as well as with the load impedance is important for an efficient (in terms of sensitivity) test system. The most accepted description of this match is the
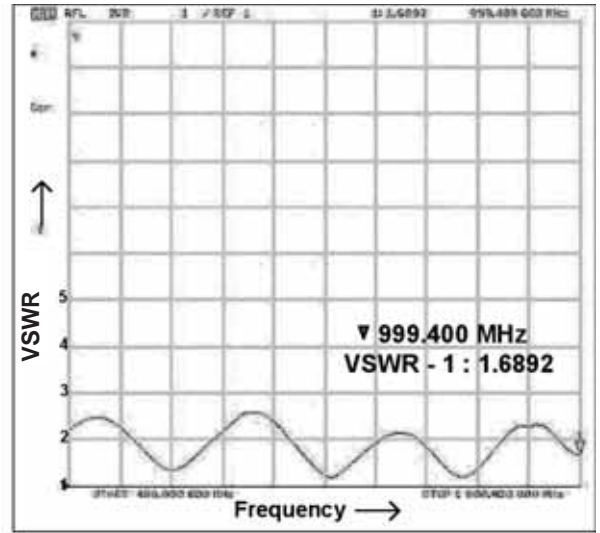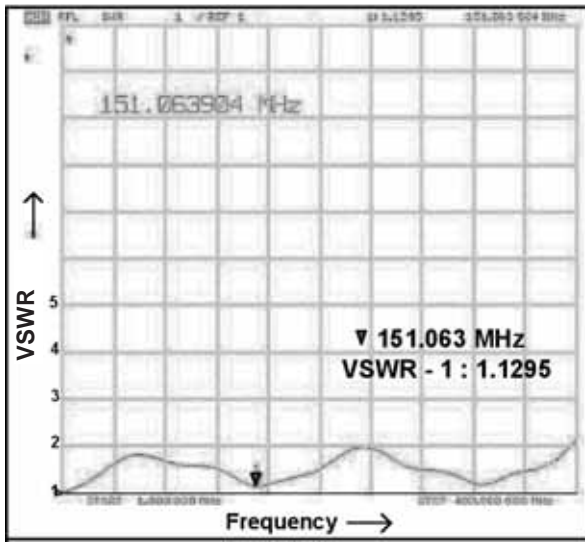
Fig. 6. VSWR measurement results of the TEM prototype, (a) In the frequency band 1–400 MHz and (b) In the frequency band 400–1000 MHz.

Voltage Standing Wave Ratio (VSWR). The ratio describes how much power will be transmitted into the antenna and how much power will be reflected back to the source. Thus, VSWR is an indication of the efficiency of the TEM cell.

(1) Voltage Standing Wave Ratio (VSWR) of the TEM Cell

In a transmission line (TEM cell is a transmission line), the ratio of the maximum to minimum voltage in a standing wave pattern is known as VSWR and it is a measure of mismatch between the transmission line and the load. It is a real number such that $1 \leq \text{VSWR} \leq \infty$. VSWR $= 1$ indicates a perfectly matched load. It has frequency dependent characteristics.

$$\text{VSWR} = \frac{V_{\max}}{V_{\min}} \qquad (5)$$

(2) Refection Coefficient of the TEM cell

The refection coefficient $|\Gamma|$ of a cell can be found using VSWR as follows;

$$|\Gamma| = \frac{\text{VSWR} - 1}{\text{VSWR} + 1} \qquad (6)$$

In terms of 'S' parameters, it is S_{11} parameter of a two-port network.

(3) Power Propagation Through the Cell

Power propagating through a TEM cell can be calculated as follows;

$$P_p = P_g \times [1 - |\Gamma|^2] \qquad (7)$$

where P_p is the power propagating through the cell (W) and P_g is the generator power (W). Thus, by measuring the VSWR and the reflection coefficient over the usable frequency range,

power through the cell can be determined. The E-field levels, inside the working volume of the TEM cell, can be estimated using (1) and (7). Figs. 6(a) and (b) show VSWR measurement results from the prototype developed in the laboratory.

In Fig. 6(a), the VSWR at 151.1 MHz is about 1.12, which is an ideal value for a practical two-port network. It is also seen that from 1 MHz–400 MHz range; it never exceeds a value of 2. In Fig. 6(b), the VSWR at 1 GHz is approximately 1.68. In the band 400 MHz–1 GHz its maximum value is 2.5. It is evident from the results that the prototype can be used from DC (0 Hz) to 1 GHz range, which is a large bandwidth.

V. DISCUSSIONS AND CONCLUSIONS

Once the cell is designed and fabricated for required characteristic impedance, it is desirable to measure the radiated emission of a product under investigation. A variety of products can be tested with a volume of $50 \times 50 \times 30$ mm^3. This could be a microcontroller with a crystal oscillator or a newly developed small digital PCB for its radiated emission signature. Most of the products have one fundamental emission peak followed by harmonic peaks. This situation is not broadband. It is ideal if a broadband source of emission is kept within the cell to measure its sensitivity for a broadband noise source. A household LPG (Liquid Petroleum Gas) gas lighter, based on high voltage arcing, is a broadband source of radiated emission (as a continuous arcing takes place in the air) and is considered as the example EUT. The gas lighter is triggered continuously inside the TEM cell prototype and emissions (corresponding voltages at the port) are measured on an EMI analyzer.

The emissions measured at the TEM cell port can be correlated with the results obtained in anechoic chamber or OATS with EMC antennas like bi-conical and log-periodic antenna by using appropriate correlation algorithms [6]–[9]. These algorithms define a measurement method and a sequence of steps to process the TEM cell measured data to obtain the value of the field as close as possible to the one that would be obtained in OATS or anechoic chamber. The method considered in [7]–[9]

encompasses two different and independent correlation algorithms for this purpose. First one is based on a 'multi-pole model' and uses a set of measurements at both the ports of the TEM cell in order to determine the equivalent multi-pole electric and magnetic moments. Both amplitude and phase information is available and a fairly accurate (<2 dB deviation) far field radiation pattern (as in OATS or semi-anechoic enclosure) can be simulated [7]. Second correlation algorithm (referred to as 'total radiated power method') uses three voltage measurements from one of the ports (the other port is terminated with a typical 50 Ω load) of the TEM Cell. The three measurements correspond to three orthogonal positions of the EUT inside the cell. In this method, the relative phase information is absent and only an upper bound estimation of radiated emission is possible. Nevertheless, it is sufficient for pre-compliance testing requirements [8]. Complete details of the 'three measurements—one port' correlation algorithm are available in standard IEC 61000-4-20 [9]. The various steps to be followed are summarized as below:

Step-1: Connect one port of the TEM cell to the spectrum analyzer and terminate the other port with a 50 Ω pad. Place the EUT inside the cell in three major (orthogonal) orientations. Corresponding to each orientation, measure the voltage at the port. The test results for one of the orientations are shown in Fig. 7. Emissions are captured from 1 MHz to 1 GHz, which is a wide bandwidth of 3 decades.

Step-2: Using the voltages measured in step-1, calculate the total radiated power from the EUT. It is given as;

$$P_T = K_1 \frac{S^2}{Z_c} \text{ (in Watts)} \qquad (8)$$

where

$$S = \sqrt{V_x^2 + V_y^2 + V_z^2} \text{ (in Volts)};$$

V_x, V_y and V_z are the measured voltages (in Volts) corresponding to the three orthogonal positions of the EUT; Z_c is the characteristic impedance of the TEM cell (typically 50 Ω);

$$K_1 = \frac{\eta_0}{3\pi} \cdot \frac{k_0^2}{e_{0_y}^2}$$

is a constant which depends upon the TEM cell geometry; $\eta_0 = 377$ Ω is the free space wave impedance in Ω; $k_0 = \frac{2\pi}{\lambda}$ is the wave number in m^{-1} (λ is the wavelength corresponding to the frequency considered);

$$e_{0_y} = \frac{E_y(x, y)}{\sqrt{P_i}} \quad \left(\text{in } \frac{\sqrt{\Omega}}{m} \right)$$

is known as the field factor. For a given test, this factor can be determined by measuring the y-component of electric field, E_y (in V/m) at the location of EUT centre (when the TEM cell is empty) with a known input power P_i (in Watts);

Step-3: The corresponding upper bound maximum field $E_{\max}$ under far-field conditions is given by;

$$E_{\max} = K_2 \sqrt{\frac{3\eta_0 \cdot P_T}{4\pi}} \quad \text{(in V/m)} \qquad (9)$$

where K_2 (in m^{-1}) is the geometry factor of the OATS or semi-anechoic shielded enclosure (a typical MIL-STD-461E enclo-
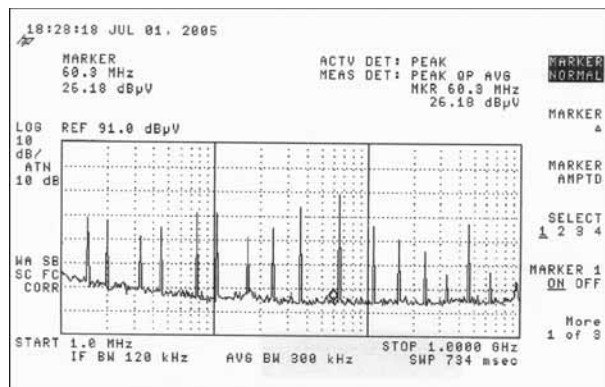

Fig. 7. Emission characteristics of a kitchen gas lighter measured in the developed prototype. Voltage (V_x) corresponding to one of the orthogonal positions of the EUT is shown.

sure) and is a function of antenna polarization (horizontal or vertical), receiving antenna distance from EUT location, height of EUT above ground plane and height of receiving antenna above ground plane.

Step-4: Steps 1 to 3 are repeated for sufficient number of points across the entire frequency band.

For the example EUT considered, the estimated values of E-field from the corresponding three voltage measurements across the desired frequency band are observed to be in agreement with the actual measured data within 6 dB, which is sufficient for pre-compliance testing. While correlating voltage and field intensity relationship, care should be taken to minimize the errors caused due to the following factors:

(1) Improper location and/or orientation of the EUT inside the TEM cell other than 3 orthogonal positions can induce large errors.

(2) Finite size of EUT can distort the field pattern inside the cell. Hence, EUT size should not be increased beyond the prescribed size limit.

(3) Similar detector functions (e.g., peak, average, rms) should be used for voltage measurements (in TEM Cell) as well as for electric field measurements (e.g., OATS) using EMI receiver.

To summarize the paper, a comparative study of stripline, TEM cell and its variant, the open TEM cell has been discussed briefly. Theory and working principle of TEM cell is revisited along with a discussion on the practical effects on the performance of the cell. A simple, economical, 'do-it-yourself' fabrication of an open TEM cell is presented. A prototype is realized using double-side fire retardant PCB and an excellent VSWR (maximum 2.5 over a wide bandwidth of DC–1 GHz) has been achieved. For the emission measurement in the fabricated prototype, a broadband noise source is kept under investigation and measurement results are presented. Since emissions from the same product can be measured in an anechoic chamber with qualified EMC antennas, a measurement correlation can always be established. In this work, the correlation has been shown using the 'radiated power method', even though other methods are also applicable. It can be concluded that the fabricated open TEM cell can be used for inexpensive in-house pre-compliance testing (both susceptibility and emission) of products during development cycle. An important use of the wide band open

TEM cell (DC–1 GHz) is found in the calibration of a D-dot sensor used for measurement of transient electromagnetic field, popularly known as electromagnetic pulse (EMP).

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BIOGRAPHIES

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Vivek Agarwal received a Bachelor's degree in Physics from Delhi University, India in 1985, a Master's degree in Electrical Engineering from the Indian Institute of Science, Bangalore, India in 1990 and a Ph.D. degree in Electrical Engineering from the University of Victoria, British Columbia, Canada in 1994. After working briefly with Statpower Technologies, Canada, he joined the department of Electrical Engineering, Indian Institute of Technology-Bombay, India, in 1995, where he is currently a Professor. His major areas of interest are power electronics and electronic systems with a focus on intelligent control of power electronic systems, power quality issues, EMI/EMC issues and non-conventional energy conditioning. He is a Senior Member of the IEEE, a Fellow of IETE and a Life Member of ISTE.