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Design and Implementation of a TEM Cell with Piecewise Linear Tapering

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Abstract— **The transverse electromagnetic (TEM) cells are used for electromagnetic interference/compatibility (EMI/EMC) experiments of the small RF devices in a laboratory environment. The standard electromagnetic fields generated in the shielded environment of a TEM cell can also be used for calibration of the RF field probes. In this paper, a 50 Ω open TEM cell is designed and fabricated to generate standard electromagnetic fields from 1 MHz up to 1 GHz. To overcome the impedance mismatch and improve the voltage standing wave ratio (VSWR) along the TEM cell, a new piecewise linear tapering method is proposed for the inner conductor of the cell. The resulted matching conditions of the new tapering method are presented through some numerical simulations and measurements and compared to those of the conventional simple linear tapering.**

Keywords- TEM Cell design; EMI/EMC experiments; calibration of RF field probes.

I. INTRODUCTION

The transverse electromagnetic (TEM) cell was invented by Crawford in 1974 [1] as an appropriate device for modeling plane wave propagation in free-space. It is used to generate standard uniform electromagnetic fields over a wide frequency range in a shielded environment. A TEM cell is a tri-plate transmission line consists of a section of square or rectangular coaxial part tapered at each end to adapt to the standard coaxial connectors. A continuous wave or a pulse generator feeds the cell at one end while a resistor equivalent to the characteristic impedance of the line terminates the cell at the other end. Both of the source and termination loads can be connected to the cell by the coaxial cables. The field propagates between the inner conductor of the cell (the septum) and the enclosure is a reasonably uniform planar field.

The TEM cells are used in electromagnetic compatibility (EMC) for susceptibility testing of the small to medium size equipment, exposing biological samples in the controlled situations, calibration of the electromagnetic field probes and sensors, measurement of the transfer functions, and research and development [2-7]. Consequently, the interest in using TEM cells has increased during the past decades and various forms of open or closed TEM cells have been fabricated depending upon the application.

An accurate cell design and fabrication can be accomplished according to the relations between the geometrical parameters and the maximum frequency of TEM-only propagation [8]. The main shortcomings of the TEM cells are their restricted working space and upper frequency limit. The TEM field propagates inside the cell up to the frequency at which the higher order modes are excited. However, this upper suitable frequency is bound by the cell physical dimensions which consequently limit the size of the items that can be tested. The issues of transition from the coaxial connector to the small rectangular cross-section terminations as well as analytical models for design of the septum at the termination are also important [9]. Furthermore, design of the transition between two straight rectangular parts of the cell needs special notification to meet the matching conditions [10]. The mismatching situation in a TEM cell results in standing waves along the structure. This means that the distribution of the electric field along the structure cannot be uniform any longer.

In this paper, we design a 50 Ω open TEM cell to generate high-voltage standard electromagnetic fields from 1 MHz up to 1 GHz and try to shape the septum of the intended cell to improve the bandwidth of the matching [11, 12]. To this end, a new method based on the piecewise linear tapering is proposed. While the conventional linear tapering cannot meet a good matching condition for the TEM cells [13], the simulation and measurement results show that the proposed tapering method cause a considerable improvement to fulfill the matching conditions for more than three frequency decades.

The organization of this paper is as follows. In Section II, a TEM cell structure is presented. The optimum design of the transition sections is described in Section III. In Section IV, the implementation of the designed cell is described. We present the simulation and measurement results in Section V. Finally, Section VI concludes the paper.

II. TEM CELL STRUCTURE

According to Fig. 1, a TEM cell is constructed from three sections: two 50 Ω coaxial lines for feeding and terminating, a 50 Ω tri-plate line, and two transition regions as intermediate media between the coaxial lines and tri-plate section. The coaxial lines are made of two cylindrical conductors with the same axis. The dominant mode of the coaxial lines is TEM. The electric field in these lines is directed radially, starts from the inner conductor and terminates at the outer conductor (and vice versa). The magnetic field in these lines circulates around the inner conductor. Similar to the coaxial lines, the dominant mode of the tri-plate section is also TEM. The electric field is perpendicularly outward from the outer conductors into the inner septum (and vice versa). In the inner space of the tri-plate section, the electric fields are formed in parallel lines, orthogonal to the metallic plates. In contrast to the electric fields, the magnetic fields are formed in parallel to the plates.

Since the TEM cell converts the radially directed electric field from the coaxial line to the uniform electric fields in the tri-plate section, a transition region is necessary to connect these two parts. Along this transition section, the distribution of the electric and magnetic fields are gradually changed from the radially directed electric field in the coaxial line to the uniform electric fields in the tri-plate section, and vice versa. Furthermore, the distributions of the magnetic fields are gradually changed from the circularly directed magnetic field in the coaxial line to the uniform magnetic field in the tri-plate section, and vice versa. This transition region must be designed such that it delivers all of the electromagnetic power received from one of these transmission lines into the other one and provide good matching in a wide range of frequencies. Any mismatch condition causes generation of standing waves along the structure and disrupts the uniform EM field distribution in the tri-plate section. In such a situation, estimation of the electromagnetic field intensities may be complicated. Accordingly, an optimum design for transition region between coaxial line and tri-plate section is necessary to achieve a matched TEM cell.

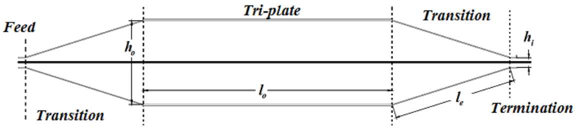

Fig. 1. Profile (side view) of a TEM cell.

Figure 2 shows the required steps to design a TEM cell. According to this figure, after specifying the required characterizations, dimensions of the tri-plate section must be determined such that its characterization impedance is equal to 50 Ω. Then, with the goal of achieving the minimum required return loss (RL) (which is -20 dB here), transition section must be optimized in the next step.

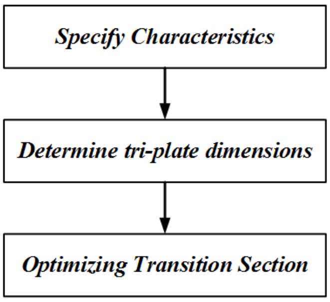

Fig. 2. Design hierarchy of a TEM cell.

III. OPTIMUM DESIGN OF TRANSITION SECTIONS

The outer part of the transition sections of the TEM cell can be shaped as a pyramid or a wedge. When the outer box of a TEM cell is shaped in the form of a pyramid, the transition region can be considered as many cascade segments of the thinner tri-plate transmission lines with decreasing dimensions from tri-plate section of the TEM cell to the coaxial line. In this shaping method, the decrease rate of the height to the width of the outer box remains constant along the transition region and consequently, fulfillment of the matching conditions is not difficult. However, when the side walls of the TEM cell is shaped as a wedge, the height of the outer conductors of the tri-plate sections is gradually reduced along the transition region while their width remains constant. We select the wedge shape for our TEM cell because of its simpler and more comfortable implementation. Furthermore, this shaping method confines the fringing electromagnetic fields and prevents radiation of power from the cell structure. The inner conductor of the transition region is designed by continuing the inner septum of the tri-plate section while the width is gradually reduced along the transition region from the tri-plate section to the coaxial feed. It should be noted that, in the wedge-shaped cell, fulfillment of the matching conditions is a difficult challenge. Therefore, our problem is how the width of the septum reduces with keeping the return loss of the structure as low as possible. To achieve this goal, all the tri-plate, feed and termination sections are modeled by uniform transmission lines with the characteristic impedances equal to 50 Ω. The transition regions are divided into smaller segments where the *k*th segment is modeled by a uniform transmission line with a characteristic impedance of Z_k which is dependent on the height, h_k, and width, w_k, of this section. According to Fig. 3, transition region has a gradual variation from tri-plate to strip line in a multi-step manner. Since the characteristic impedances in the both sides of the transition region are equal to 50 Ω, the Z_k characteristic impedances must be equal to 50 Ω to minimize the return loss. The characteristic impedance of the *k*th segment is given by [11, 14];

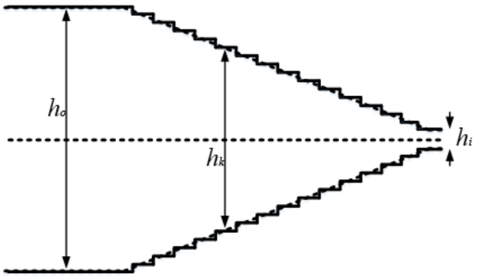

Fig. 3. Side view of the TEM cell discretized into uniform tri-plate sections, (the height is reduced in a multi-steps way from tri-plate to coaxial line).

$$Z_k = \frac{V_k}{I_k} = \frac{-\int_s^o \overrightarrow{E}_k.\overrightarrow{dl}}{\oint_C \overrightarrow{H}_k.\overrightarrow{dl}} \qquad (1)$$

where V_k and I_k are the voltage between the septum and the outer box and the current flowing in the septum, respectively. For calculating V_k, an integration is taken from the septum to the outer box. Furthermore, I_k can be obtained by an integration on the closed contour around the septum. Then, equation (1) can be written as:

$$Z_k = \eta_0 f\left(h_k, w_k\right) \qquad (2)$$

where η_0, is the characteristic impedance of the free space. In general, f is a nonlinear function which is dependent on the distribution of the electromagnetic field in the structure. Therefore, in designing a TEM cell, the width of the septum must be determined so that all Z_k impedances are equal to 50 Ω.

The physical dimensions of the outer box of the TEM cell are obtained by considering its characteristic impedance and usable frequency range and presented in Table I. According to Fig. 1, the parameters a and w are the width of the outer box and the septum, respectively. The parameters l_o and h_o are determined to provide sufficient measurement space for the test devices. The type of the connector used in the structure limits the value of h_i. The value of w is determined to provide a characteristic impedance of 50 Ω at the tri-plate section. The edges of the outer conductors of the tri-plate section are continued shortly in a right angle to increase the mechanical stability.

The linear tapering of the septum with a constant rate and a triangular shape is more conventional. The tapering starts at the tri-plate section and terminates at the inner conductor of the coaxial line. However, as previously mentioned, this tapering style cannot provide a good matching for wideband applications. Any deviation of the characteristic impedance of the transition section from 50 Ω may avoid satisfaction of the required matching conditions in a wide bandwidth. As the physical dimensions of the structure play an important role in the characteristic impedance of the transmission line, it is possible to improve the characteristic impedance of the transition section by proper shaping of the septum. In this paper, we propose a new tapering style named as piecewise linear tapering to provide a wideband matching along the TEM cell. As shown in Fig. 4, in this tapering method, a few points are selected on the edge of the septum and each point is connected to the neighboring points by straight lines. The number of points and their locations are obtained after repeating optimization/simulation for fulfillment of the matching conditions. With the goal of achieving a RL less than -20 dB in the intended frequency range, 5 points are selected in the edge of the septum and their locations are optimized. The final physical locations of these points ($P_i(x_i, y_i)$ for i=0,1,…,6) are given in Table II. All points are determined relative to P_0 (according to Fig. 4, the origin of the coordinate system, P_0, is the middle point of the thinner part of the septum).

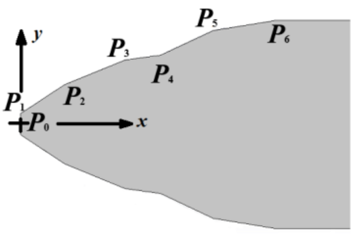

Fig. 4. Piecewise linear tapering of the septum.

TABLE I. Physical dimensions for the outer box of the TEM cell (all dimensions are in millimeter).

a	l_o	l_e	h_i	h_o	w
225	600	223	17	150	210.6

TABLE II. Physical dimensions of the TEM cell with piecewise linear tapering (all dimensions are in millimeter).

x_0	x_1	x_2	x_3	x_4	x_5	x_6
0	0	49.3	110.3	146.3	199.3	277.3
y_0	y_1	y_2	y_3	y_4	y_5	y_6
0	10.6	29	56	70.5	95.22	105.3

IV. IMPLEMENTATION OF TEM CELL

The designed TEM cell is fabricated according to the physical dimensions presented in the previous section. As it is seen in Fig. 1, the cell is constructed from the outer sidewalls (at the top and the bottom) and the septum. All these parts are made of 1-mm thick plates of Aluminum. Figures 5 and 6 show the septum and the fabricated TEM cell, respectively. Four spacers, made of Plexiglas, are used to fix the position of the septum and the outer sidewalls.

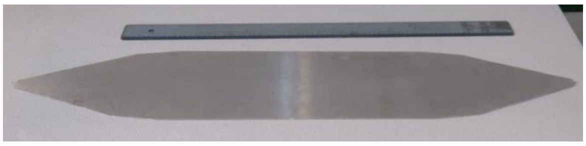

Fig. 5. Septum of the TEM cell.

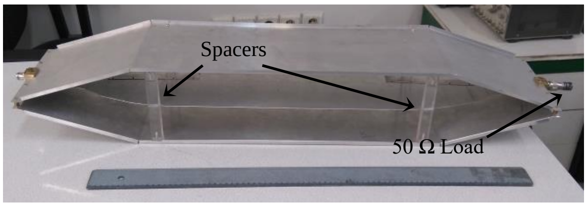

Fig. 6. View of the fabricated TEM cell.

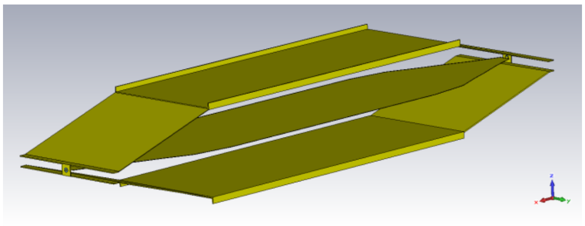

Fig. 7. The simulated TEM cell in CST.

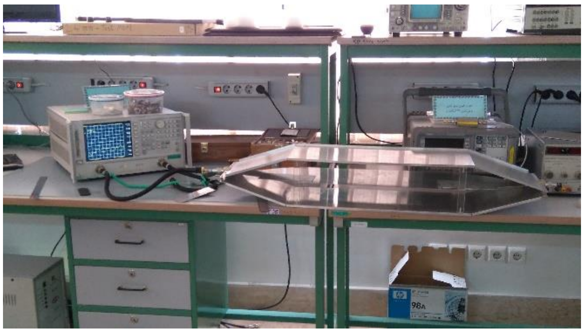

Fig. 8. The measurement setup used for measuring RL and IL of the TEM cell.

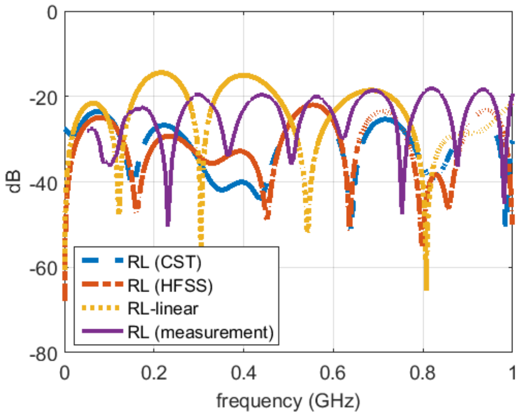

Fig. 9. Return loss of the TEM cell.

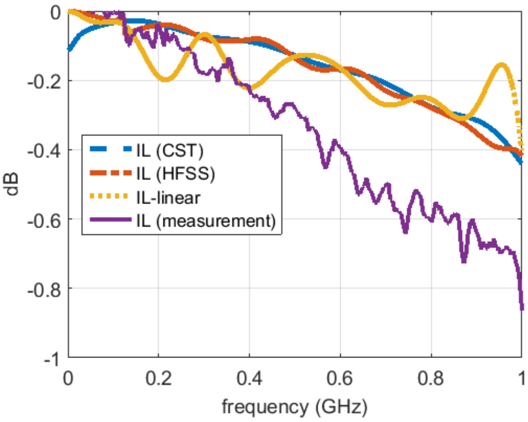

Fig. 10. Insertion loss of the TEM cell.

V. SIMULATION AND MEASUREMENT RESULTS

In this section, the simulation and measurement results of the designed TEM cell is presented. Two solvers are applied to simulate the structure: Finite Integral Technique (FIT), and Finite Element Method (FEM). While FIT gives a direct solution of the Maxwell's equation in the time domain by discretizing the structure in hexahedral meshes, FEM is a numerical method in the frequency domain that decomposes the structure into the tetrahedral cells. The structure is simulated by both of the commercial CST and HFSS tools. Figure 7 shows a 3D view of the structure in CST. Furthermore, Fig. 8 shows the setup used for measuring the RL and insertion loss (IL). An Agilent 8722ES vector network analyzer is used in this measurement. The frequency variation of the RL is shown in Fig. 9. The simulation results for RL of a TEM cell with linear tapering is also presented for a better comparison.

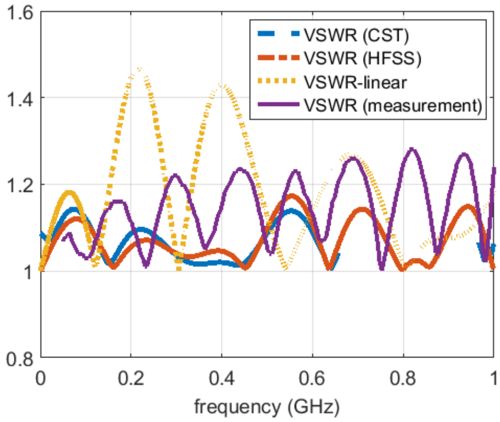

Fig. 11. VSWR of the TEM cell with piecewise linear transition.

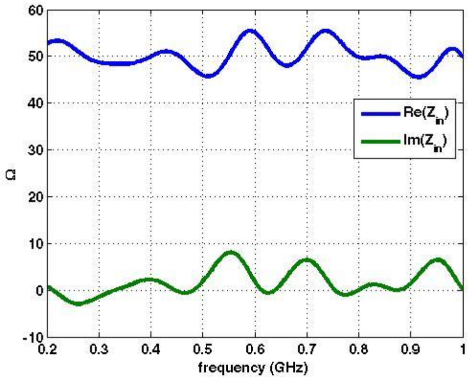

Fig. 12. Input impedance of the TEM cell with piecewise linear tapered septum.

Fig. 10 shows the frequency variations of the IL. The resulted VSWR of the piecewise linear tapered structure is shown in Fig. 11. Both of these results are compared with those related to the linear tapering. It can be observed from these figures that the piecewise linear tapering results in a better matching condition relative to the linear transition. The impedance seen from input port of the TEM cell is shown in Fig. 12. As shown, the real part of input impedance oscillates around 50 Ω, while the variation of imaginary part of input impedance is bounded around zero.

Figure 13 shows the variation of the electric field in the inner space of the tri-plate section of the TEM cell at three different frequencies of 100 MHz, 500 MHz and 1 GHz. It is seen that the electric field distributions are formed uniformly along the transverse plane in a wide range of frequencies.

The experimental results of measuring electric field in the TEM cell are shown in Fig. 14. A Wavecontrol WPF6-SMP2 field strength meter is used for this measurement. In theory, the electric field in the TEM cell must be 4.2 V/m when the net power delivered to the TEM cell (P_{in}) is 3 dBm. In Fig. 14, E_{max} and E_{min} are the maximum and minimum electric field measured in the TEM cell, respectively. Different factors, for example, standing waves in the TEM cell due to mismatching, holders used as a fixture, some field distortion due to the inserting probe, result in these variations [15].

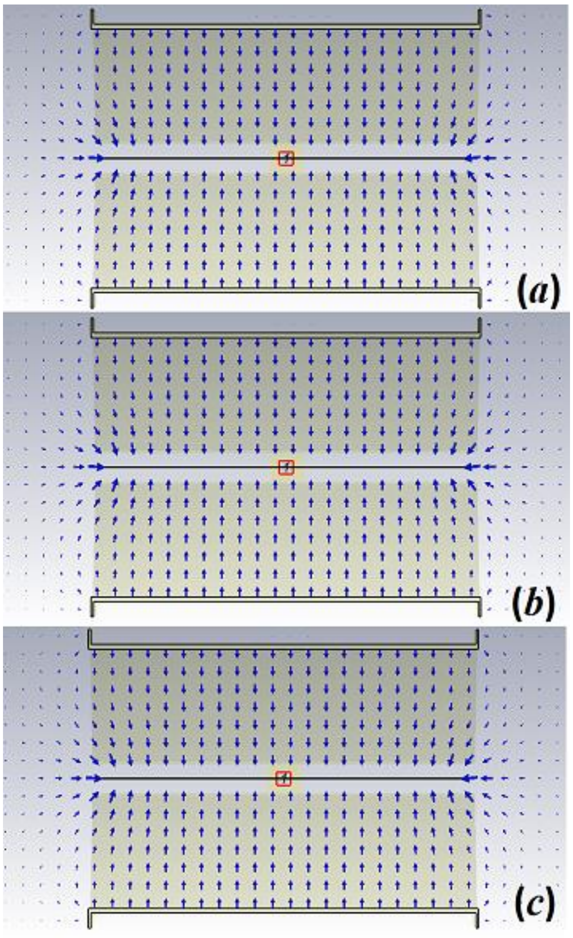

Fig. 13. Electric field distribution at transverse plane; (a) 100 MHz, (b) 500 MHz, and (c) 1 GHz.

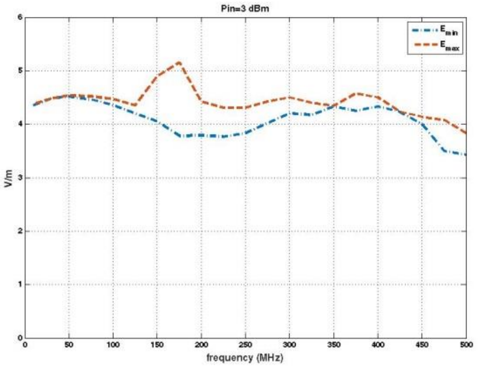

Fig. 14. The variation of electric field in TEM cell.

VI. CONCLUSION

In this paper, a new design method, named as piecewise linear tapering, has been proposed to taper the inner septum of a wedge-shaped TEM cell. This TEM cell is fabricated for calibration of the RF field probes. The simulation and measurement results indicate that the piecewise linear tapering can achieve a broadband matching relative to the conventional linear tapering. The low number of shaping points needed in this method helps the designers optimize the structure with little computational resources. It also helps for simple compensation of the errors created in the manufacturing processes of the structure.

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