Turk J Elec Engin, VOL.11, NO.2 2003, © TÜBİTAK

Design of a TEM-Cell with Increased Usable Test Area

Kresimir MALARIC, Juraj BARTOLIC
Faculty of Electrical Engineering and Computing, Unska 3, HR-10000 Zagreb, Croatia
e-mail: kresimir.malaric@fer.hr

Abstract

Transversal electromagnetic mode cells (TEM-cells) are used for electromagnetic compatibility measurements (emission and immunity), and for biomedical applications. Over the years, higher and higher frequencies are being used, which demands smaller transmission structures in order to obtain the homogeneous field distribution due to resonance. Such resonance destroys the TEM field, introducing higher order modes. The goal was to design the TEM-cell for GSM frequencies that will have a larger area with a homogeneous field used for testing, while still obtaining the characteristic impedance. Commercial TEM-cells used for frequencies of 900 MHz have only 2 cm in height available for testing, while the proposed TEM-cell has 5 cm in vertical dimension suitable for EMC testing. The problems regarding characteristic impedance, resonance, higher order modes, dimensions and usable test area are discussed. Numerical modeling with the "Quickfield", which uses finite element method (FEM), and "MAFIA", which uses finite integration technique (FIT) gave the electromagnetic field distribution and calculation of the higher order modes. The measurements of VSWR and insertion loss showed good correlation with the model. At 935 MHz, the VSWR is 1.1 which makes the cell applicable for GSM frequencies. The higher order modes appear at 490 MHz and 740 MHz, but another frequency area is usable. The TEM-cell has a characteristic impedance of 75 Ω and an increased usable test area. It can be utilized for EMC measurements and biomedical applications from DC to 1 GHz.

1. Introduction

Since 1974 and the introduction of the transversal electromagnetic cell (TEM-cell) [1], there has been many improvements and different variations of transmission line cells for EMI and EMC testing. With the increasing frequency of usage, this quest will continue.

Transverse electromagnetic (TEM) transmission line cells (Figure 1) are devices used to establish standard electromagnetic (EM) fields in a shielded environment. They are triplet transmission lines with the sides closed to prevent radiation of RF energy into the environment and to provide electrical isolation. The cell consists of a section of rectangular coaxial transmission line tapered at each end to adapt to standard coaxial connectors. A uniform TEM field is established inside a cell at any frequency of interest below that for which higher order modes begin to propagate. TEM-cells are used for the emission testing of small equipment, for the calibration of RF probes and for biomedical experiments. The wave traveling through the cell has a free-space impedance (377 Ω), thus providing a close approximation of a far-field plane propagating in free-space. The cells are broadband having a linear phase and amplitude response from DC to the cell's cutoff frequency. This characteristic allows continuous-wave (CW) or swept-frequency, as well as impulsive and modulated signal testing, to be performed. The cell has its limitations. The main is that the upper useful frequency is bound by its physical dimensions, which in turn constrain the size of item that can be tested.

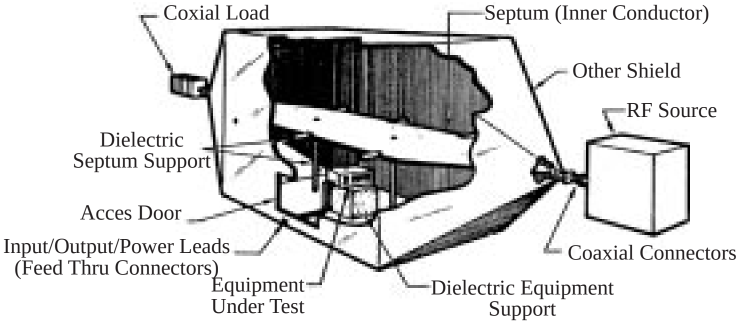

Figure 1. TEM-cell.

With a TEM-cell, the higher order modes appear at sharply defined frequencies. The exact determination of the cut-off and the resonant frequencies has been thoroughly investigated for some time now [2]. The appearance of the resonant frequencies destroys the uniform field distribution inside the cells. With the frequency increasing, the size of the cell becomes smaller. The goal was to design TEM-cell for a frequency of about 900 MHz with a large area for equipment testing, while maintaining the standard characteristic impedance (50 or 75 Ω). TEM-cells can be used for experiments in electromagnetic compatibility, namely for emission and conductivity testing, and for biomedical applications. Emission testing measures the level of radiation from a certain electronic device, while conductivity (immunity) measures the amount of radiation that certain equipment or electronic device can withstand while still operating within their limits. Biomedical applications include in-vivo and in-vitro experiments on plants, tissue and live animals (rats i.e.)

2. Design of TEM-Cells

A TEM-cell (and most cells) is usually designed to have 50 Ω of characteristic impedance, with $a > b$ (Figure 2). Only one-third of the area between the septum and the shield is usable for the testing. The commercial TEM-cells can be used basically only for the calibration of RF probes due to their small vertical size of 6 cm between the septum and top shielding, which gives only a 2 cm vertical size available for experiments on the 900 MHz frequency. Their characteristic impedance is 50 Ω. The dimensions of our cell were chosen in a way that $a < b$, thus achieving more space in the vertical dimension. In our case, $w/a = 0.72$, and $a/b = 0.83$. This resulted in a characteristic impedance of 75 Ω [3]. Although most network analyzers have 50 Ω impedance, a match can be made with 50 Ω/75 Ω transformers. The proposed TEM-cell has 15 cm available between the septum and the shield, which gives us 5 cm area usable for testing. The material is aluminum, except for the septum made of copper. The size issue is very important because it allows us to place larger instruments or equipment to be tested inside without disturbing the homogeneous electromagnetic field. In this way, we save on overall cost, while at the same time increasing the usable frequency span.

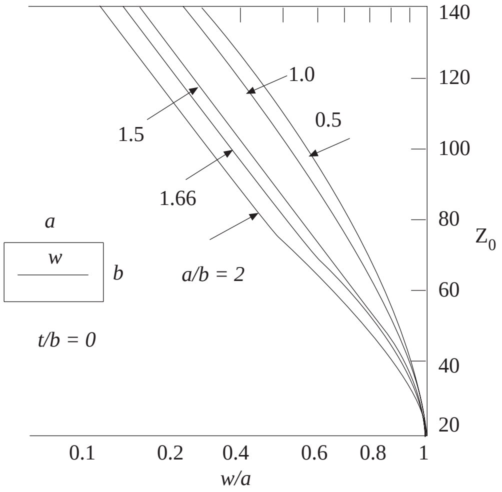

Figure 2. Z_0 versus w/a for various a/b values ($t/b = 0$).

2.1. Characteristic impedance

The characteristic impedance of the transmission line has been given by Crawford [1] in terms of the fixed dimensions of the line's cross section (Figure 3) as well as an unknown fringing capacitance per unit length C'_f

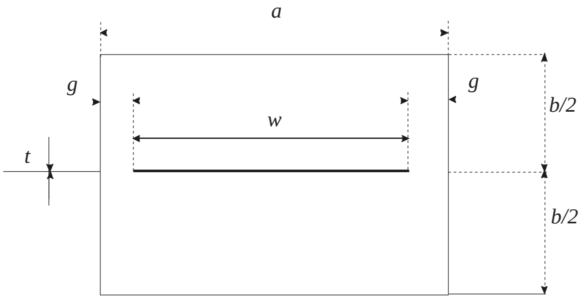

Figure 3. 75 Ω TEM-cell line cross section.

$$Z_0 = \frac{376,73}{4[w(b-t) + Cf'/\varepsilon]} \tag{1}$$

where $\varepsilon = 8{,}852\ 10^{--12}$ F/m, assuming an air dielectric. For a center conductor with finite but small thickness,

$$\frac{Cf'}{\varepsilon} = \frac{2b}{\pi(b-t)} ln \left[1 + coth \left(\frac{\pi}{2} \frac{a-w}{b-t} \right) \right] + \frac{t}{a-w} ... \tag{2}$$

The above equation is valid for $(a-w)/2b < 0.4$. The equations for zero thickness center conductor and with center conductor $t/b > 0.2$ can be found in [4].

While designing the cell, after taking into the account its future purposes, such as biomedical exposures as well as RF probe calibration and EMC, the dimensions of the cell had to be chosen to ensure the largest possible test area for frequencies of around 900 MHz, while maintaining standard characteristic impedance. Dimensions were chosen in a way that $a < b$, thus achieving more space in the vertical dimension. This resulted in a characteristic impedance of 75 Ω. Figure 4 shows the diagram of TEM cell designed at FER.

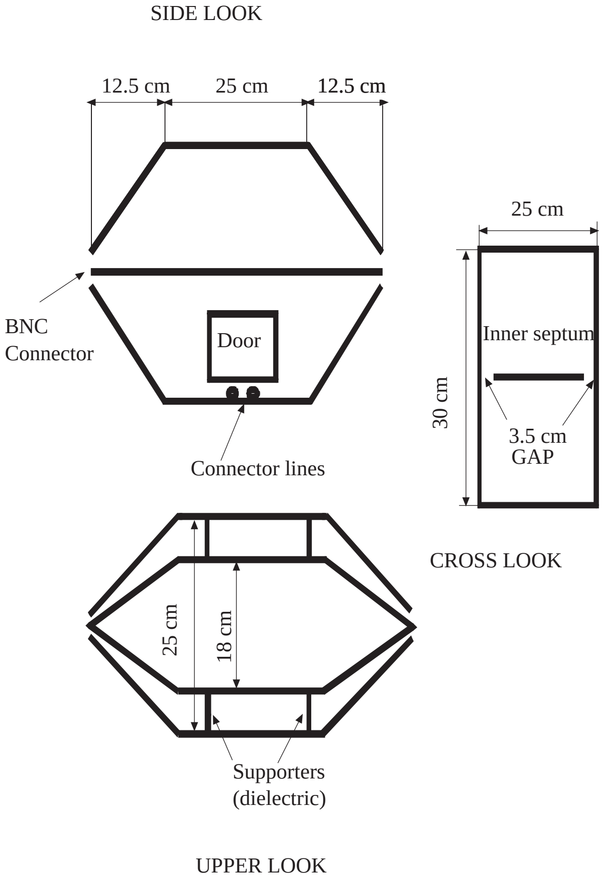

Figure 4. Diagram of 75 Ω TEM-cell.

3. Numerical Modeling

In our work, two numerical methods have been used: finite element method (FEM) and finite integration technique (FIT). FEM was used for the electric and magnetic field calculation inside the TEM-cell, and FIT was used for the calculation of the higher order mode frequencies.

3.1. Finite Element Method

FEM is used to solve complex, nonlinear problems in magnetics and electrostatics [5]. The first step in finite-element analysis is to divide the configuration into small homogeneous elements. Finite-element model is shown in Figure 5. The model contains information about device geometry, material constants, excitations and boundary constraints. The elements are small where geometric details exist, and are much larger in other places. In each finite element, a linear variation of the field quantity is assumed. The corners of the elements are called *nodes*. The goal of the finite-element analysis is to determine field quantities at the nodes.

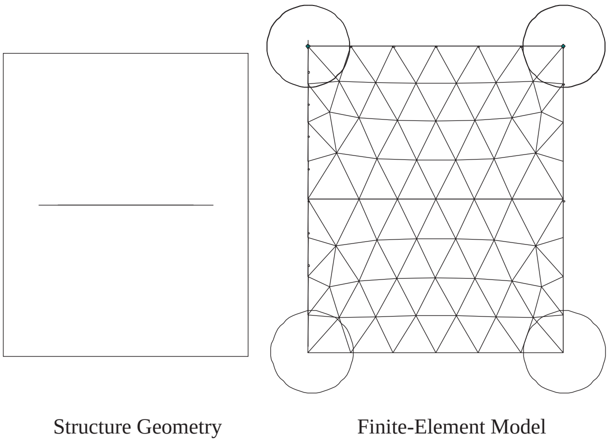

Figure 5. FEM example for TEM-cell.

Finite-element analysis techniques solve the unknown field quantities by minimizing an energy functional. The energy functional is an expression describing all the energy associated with the configuration being analyzed. For three-dimensional, time-harmonic problems this functional may be represented as

$$F = \int_v \frac{\mu\,|H\,|^2}{2} + \frac{\varepsilon\,|E\,|^2}{2} - \frac{J \cdot E}{2j\omega} dv \tag{3}$$

The first two terms in the integrand represent the energy stored in the magnetic and electric fields and the third term is the energy dissipated (or supplied) by conduction currents.

Expressing H in terms of E and setting the derivative of this functional with respect to E equal to zero, an equation of the form $f\,(J\,,E\,) = 0$ is obtained. A kth order approximation of the function f is then applied at each of the N nodes and boundary conditions are enforced, resulting in the system of equations

$$\begin{bmatrix} J_1 \\ J_2 \\ \cdot \\ \cdot \\ J_n \end{bmatrix} = \begin{bmatrix} y_{11}\ y_{12}\ \cdot\ \cdot \\ y_{21}\ y_{22}\ \cdot\ \cdot \\ \cdot\ \cdot\ \cdot\ \cdot \\ \cdot\ \cdot\ \cdot\ \cdot \\ \cdot\ \cdot\ \cdot\ y_{nn} \end{bmatrix} \begin{bmatrix} E_1 \\ E_2 \\ \cdot \\ \cdot \\ E_n \end{bmatrix} \tag{4}$$

The values of J on the left side of this equation are the source terms. They represent the known excitations. The elements of the Y-matrix are functions of the problem geometry and boundary constraints. Since each element only interacts with elements in its own *neighborhood*, the Y-matrix is sparse. The terms of the vector on the right side represent the unknown electric field at each node. These values are obtained by solving the system of equations. Other parameters, such as the magnetic field, induced currents and power loss, can be obtained from the electric field values.

In order to have a unique solution, it is necessary to constrain the values of the field at all boundary nodes. The metal box of the model in Figure 5 constrains the tangential electric field at all boundary nodes to be zero. The electrical and geometric properties of each element can be defined independently. Figure 6 shows results of numerical modeling analysis (note: higher values are represented by warmer colors [brighter]). The model is valid for the TEM mode, which means below the frequencies where higher order modes start to appear.

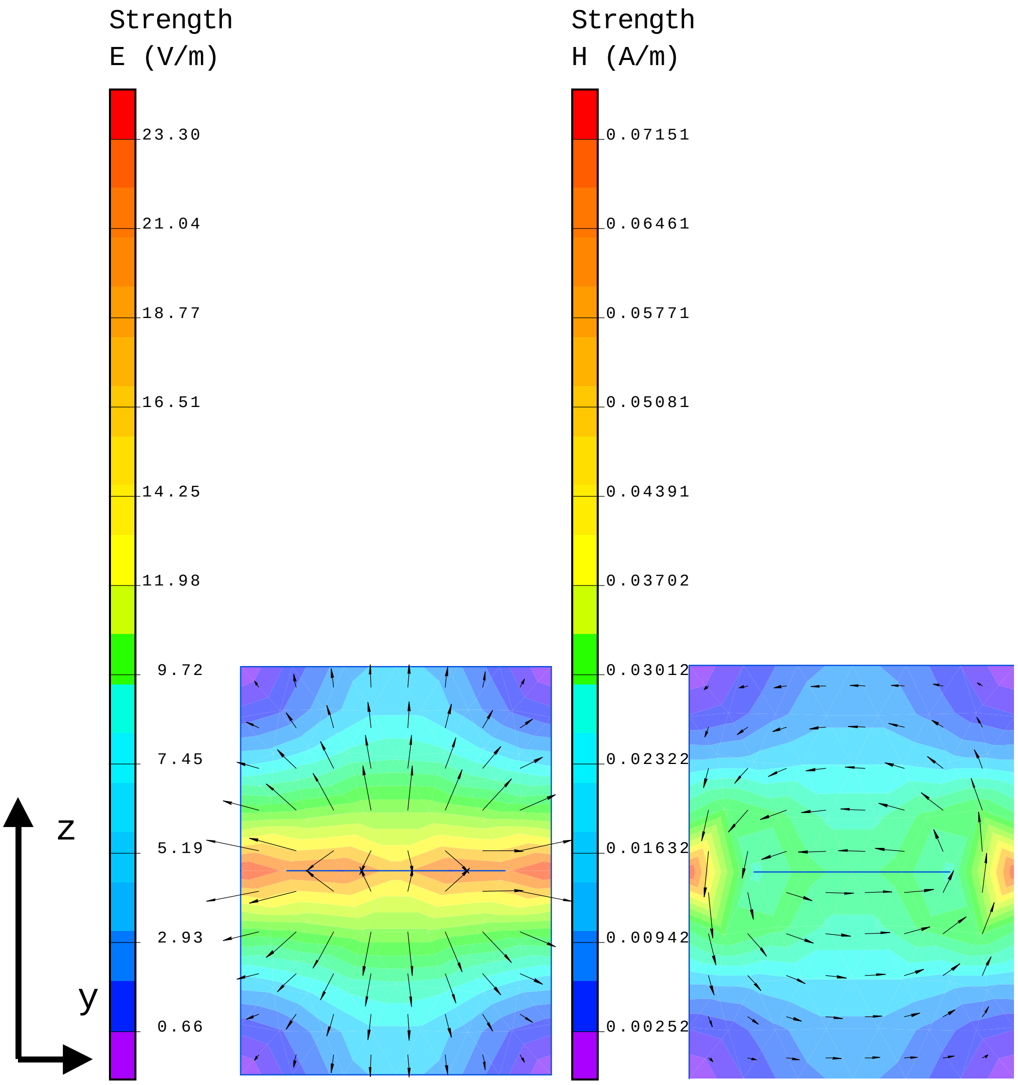

Figure 6. a) Strength and vectors of **E**, b) strength and vectors **H**.

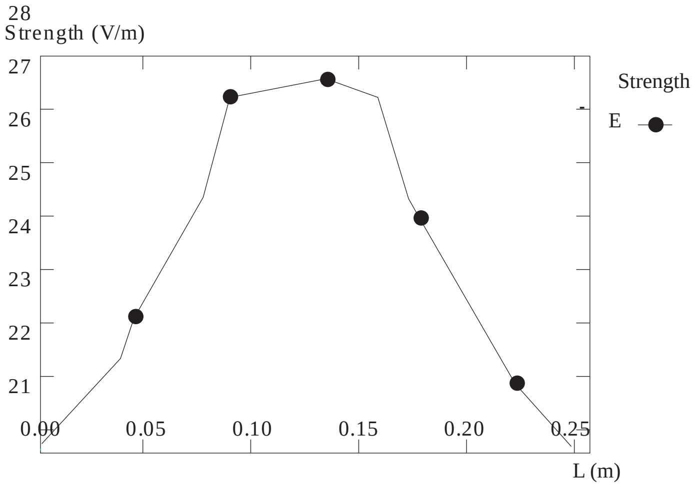

Figure 6. c) Distribution of electric field at 1/2 septum height.

Figure 6a shows the strength and vectors of an electrical field, and Figure 6b for a magnetic field. It can be seen that the area below (and above) the septum has the homogeneous field distribution. The colors (shade) represent the intensity of the electric or magnetic fields. Figure 6c shows the electric field distribution along the y axis, and for the input power of 13 dbm it gives the electric field of around 15 V/m in the area that is used for testing. When the EUT is inserted, the electromagnetic field will suffer a certain distortion, depending on the dielectric characteristics of the material. It does not matter whether the EUT is made of metal or dielectric material. However, even the insertion of the RF probe distorts the electromagnetic field distribution somewhat. The influence of the EUT can be evaluated if we measure (or model) the field before and after the insertion of the EUT on the same place, and use this correction when dealing with the results.

3.2. Finite Integration Technique

Finite Integration Method is implemented in a computer program "MAFIA", which was used for the numerical modeling of TEM-cells. FIT [9] combines the advantages of the frequency and time division analysis methods. It is similar to the FDTD, except that it is based on the solving of Maxwell equations in an integration form rather than the differential form used in FDTD (Figure 7).

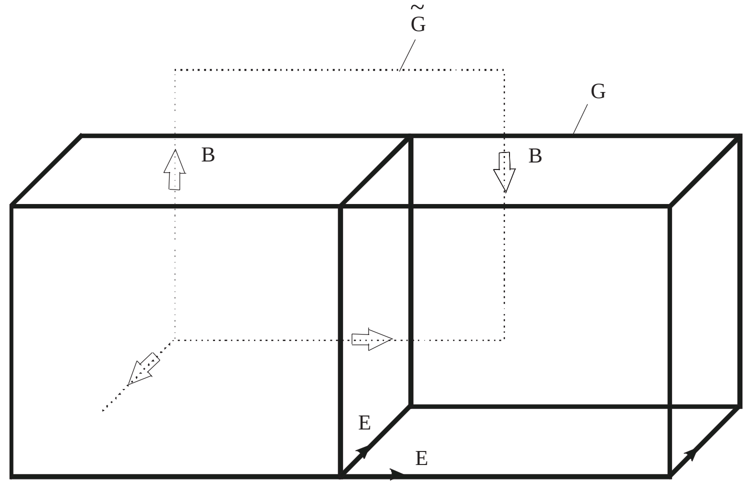

Figure 7. FIT.

The analytical equations are discretized onto two grids orthogonal to each other. This gives us a set of matrix equations, where each is the discrete analog to one of the original Maxwell equations

$$\oint_{\partial A} E \cdot d\overrightarrow{s} = \int\int_{A} \frac{\partial B}{\partial t} \cdot dA \Leftrightarrow CD_s e = -D_A b \tag{5}$$

$$\int_{\partial A} H \cdot d\overrightarrow{s} = \int\int_{A} \left(\frac{\partial D}{\partial t} + J \right) \cdot dA \Leftrightarrow \tilde{C}\tilde{D}_S h = \tilde{D}_A \dot{d} + j \tag{6}$$

$$\oiint_{\partial V} \left(\frac{\partial \mathbf{D}}{\partial t} + \mathbf{J} \right) \cdot dA = 0 \Leftrightarrow \tilde{S}\tilde{D}_A(\dot{d} + j) = 0 \tag{7}$$

$$\begin{array}{c} \mathbf{D} = \varepsilon\mathbf{E} \Leftrightarrow d = \tilde{D}_{\varepsilon} e \\ \mathbf{B} = \mu\mathbf{H} \Leftrightarrow b = \mathbf{D}\mu h \end{array} \tag{8}$$

$$\begin{array}{l} J = \kappa E + \rho v \Leftrightarrow j = \tilde{D}_{\kappa} e + D_{\rho} v \\ div \quad (rot) = 0 = \nabla \cdot (\nabla x \cdot) \Leftrightarrow SC = \tilde{S}\tilde{C} = 0 \end{array} \tag{9}$$

$$rot \quad (grad) = 0 = (\nabla x) \cdot \nabla \Leftrightarrow C\tilde{S}^t = \tilde{C}S^t = 0 \tag{10}$$

where E and H are the electric and magnetic field values, respectively; ε and μ are permitivity and permeability, respectively; J is the current density; ρ is the charge density; κ is conductivity; A is the surface area; s is the length; and v is the charge velocity.

The main characteristics are the preservation of all analytical properties of the Maxwell equations, retaining their physical and mathematical characteristics.

4. Measurements

Measurements on the TEM-cell were performed with respect to VSWR and return loss. VSWR (Figure 8) shows that although the first higher mode appears at 485 MHz, there are still gaps where the TEM-cell can be used (around 635 MHz and 935 MHz). The size of the TEM-cell would normally allow its use until the first cut-off frequency, which depends on the vertical size of the cell. In this case, it is increased due to the geometry. The characteristic impedance is not 50 Ω, but 75 Ω, which is still the standard characteristic impedance. Figure 9 shows the return loss and the notches at the same frequency as shown in Figure 8. Figure 10 shows the Smith chart of the same measurements. The measurements were performed with the HP network analyzer 8720 B.

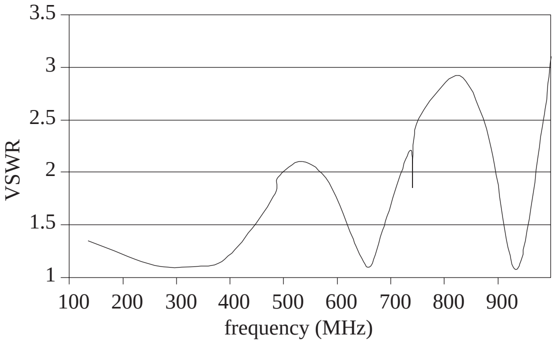

Figure 8. VSWR.

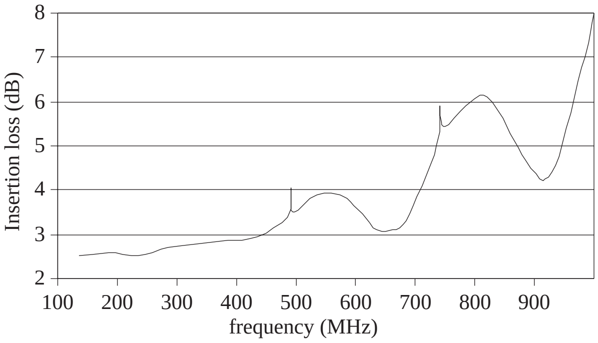

Figure 9. Insertion loss.

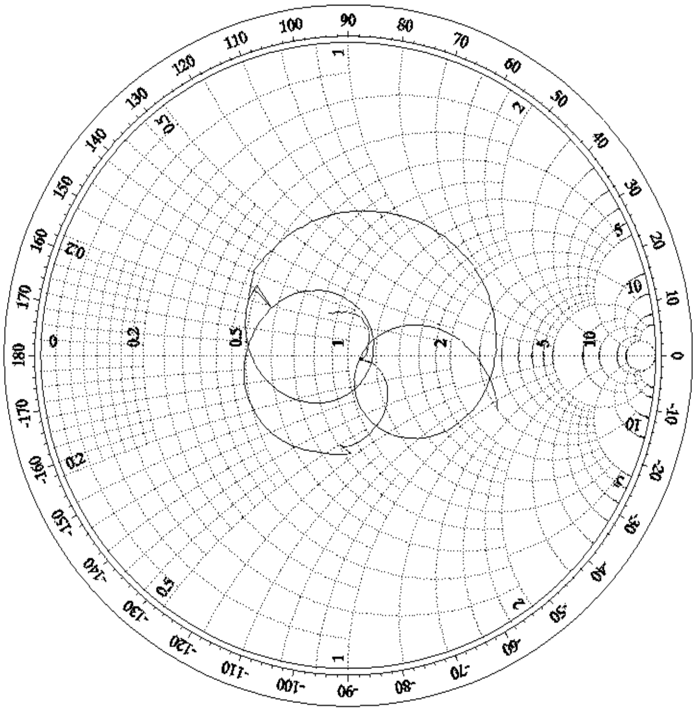

Figure 10. Smith diagram of TEM cell with transformers.

5. Higher Order Modes

A basic TEM-cell limitation is the appearance of resonance, which tends to destroy the desired TEM-mode field distribution. There are numerical solutions for the normalized cutoff frequency of the initial higher order modes as a function of the inner conducting width. However, determining the resonant length of a cell is nontrivial since the tapered sections affect each higher order mode differently. Because a TEM-cell is a high-Q cavity, the higher order resonances appear at sharply defined frequencies. Thus, there may exist windows between resonance levels where TEM-cell usage is still quite valid. To what extent these structures are usable when higher order mode resonance is present and whether or not they are usable at frequencies between such resonance depends very much on the particular application for which the cell is being used.

The cutoff frequency for TE_{10}, usually the first higher order mode, is given by

$$f_c(TE_{10}) = \frac{c}{2a} \tag{11}$$

where c is the velocity of light. The equation for the cutoff frequency for any higher mode is

$$f_c(TE_{mn}) = \frac{c(b^2m^2 + a^2n^2)^{1/2}}{2ba} \tag{12}$$

The TEM-mode propagates through the tapered ends of the cell without significant change. Each higher mode is always reflected at some point within the taper where it becomes too small to propagate the mode. The propagating energy in the higher-order mode undergoes multiple reflections, end to end, within the cell until it is dissipated. At certain frequencies, a resonance condition is satisfied, in which the cell's effective length for the mode is "p" half guide wavelengths long (p = 1,2,3, ...). At the resonant frequencies, $f_{R(mnp)}$, a TE$_{mnp}$ resonant field pattern exists [6]. Using

$$l(mn) = p\lambda_{g(mn)}/2;\ p = 1, 2, 3 \tag{13}$$

and

$$\frac{1}{\lambda^2} = \frac{1}{\lambda_{g^2}} + \frac{1}{\lambda^2_{c(mn)}} \tag{14}$$

where $\lambda_{c(mn)}$ represents the cutoff wavelength value, the following expression by which various resonant frequencies can be predicted, is given by

$$f^2_{R(mnp)} = f^2_{c(mn)} + \left(\frac{pc}{2l_{(mn)}}\right)^2 \tag{15}$$

where $f_{c(mn)} = c/\lambda_{c(mn)}$ [7].

The resonant frequencies, shown in the Table, have been obtained for the TEM-cell: 490 MHz and 740 MHz. The results of the measurements correlate with the results obtained with the software tool "MAFIA", as can be seen in the Table. As we can see, the first higher order modes start to appear at around 500 MHz, but the TEM-cell can still be used on the higher frequencies, because the resonances are sharp and there are frequency gaps where the cell is still usable.

Table Higher order modes in TEM-cell.

Mode	Measured	"MAFIA"
TE$_{01}$	490 MHz	460.69 MHz
TE$_{10}$	740 MHz	735.60 MHz

"MAFIA" [8] uses FIT [9], which combines the advantages of time and frequency domain. It is similar to the FDTD method, except that it is based on solving Maxwell equations in an integral form compared to the differential form used in the FDTD method. The main characteristic is that all of the analytic factors of Maxwell equations are preserved, keeping at the same time physical and mathematical characteristics.

Extension of the useful frequency range of the cell can be done by absorber loading. This is achieved by lowering Q inside the cell, which depends on frequency. The absorber improves the uniformity of the field between the septum and top or bottom walls by increasing the vertical component of the electrical field at the edges of the septum, but introduces transmission losses.

6. Application

A HP 8657A signal generator, MiniCircuits 5W amplifier and TEM-cell (Figure 11) designed at FER are used for the undergoing biomedical application experiments. In cooperation with the Institute of Medical Research, Zagreb we are investigating the influence of mobile frequency electromagnetic fields on the growth of lung cells. The larger area used for testing enables more biological tissue to be inserted for experimentation, thus shortening the measurement time.

Figure 11. Instrumentation for the measurements.

7. Conclusion

Numerical modeling with FEM was performed and the results of the potential line and strength of E and H were presented. This modeling is important prior to the building of the cells and to see what is happening inside the cell at the area of measurement and as a comparison with the measured results.

TEM-cells can be used for biological exposure and EMC measurements up to 1 GHz. At 935 MHz, measurements can be performed with biological materials (bacteria, for example) to observe the effect of GSM and EMC measurements (small IC or electronic devices). The ratio of $a/b = 0.833$ enables a larger usable test area, while characteristic impedance is 75 Ω instead of the 50 Ω used in most TEM-cells. Although higher order modes start to appear above 500 MHz, the cell can still be used at higher frequencies, because there are gaps with the uniform TEM-field above the first cutoff frequency, one being around 900 MHz.

References

[1] M.L. Crawford, “Generation of Standard EM Fields Using TEM Transmission Cells”, IEEE Trans. on Electromagnetic Compatibility, Vol. EMC-16, No. 4, pp. 189-195, 1974.

[2] P.F. Wilson, M.T. Ma, C.M. Weil, L. Gruner, “Simple Approximate Expressions for Higher Order Mode Cutoff and Resonant Frequencies in TEM Cells”, IEEE Trans. on Electromagnetic Compatibility, Vol. EMC-28, No. 3, pp. 125-130, 1986.

[3] K. Malaric, J. Bartolic, “TEM-Cell with 75 Ω Impedance for EMC Measurements”, IEEE 1999 International Symposium on Electromagnetic Compatibility, Proceedings Vol. 1, Seattle, WA, USA, pp. 234-238, 1999.

[4] C.M. Weil, “The Characteristic Impedance of Rectangular Transmission Lines with Thin Center Conductor and Air Dielectric”, IEEE Trans. on Microwave Theory and Techniques, Vol. MTT-26, No. 4, pp. 238-242, 1978.

[5] T.H. Hubing, Survey of Numerical Electromagnetic Modeling Techniques, Report Number TR91-001.3, University of Missouri-Rolla, EMC Laboratory, 1991.

[6] M.L. Crawford, J.L. Workman, C.L. Thomas, “Expanding the bandwidth of TEM Cells for EMC”, IEEE Trans. on Electromagnetic Compatibility, Vol. EMC-206, No. 3, pp. 368-375, 1978.

[7] C.M. Weil, L. Gruner, “High-Order Mode Cutoff in Rectangular Striplines”, IEEE Trans. on Microwave Theory and Techniques, Vol. MTT-32, No. 6, pp. 638-641, 1984.

[8] MAFIA - Manual, CST, Germany, 1997.

[9] E. Tanabe, P. Hahne, “The FIT Approach Enhances EM Simulation Capability”, Microwaves & RF, pp. 102-108, 1997.