A New TEM Cell: Test Results Up To 3 GHz and a Comparison to Alternative Solutions

Frequency range and field uniformity are important considerations in the development of test cells.

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INTRODUCTION

Transverse electromagnetic (TEM) cells were introduced several years ago.[1] They were primarily conceived as devices for radiated immunity testing, in which an equipment under test (EUT) is subjected to the electromagnetic (EM) field of the TEM mode propagating in a coaxial strip line. The key point is that the TEM mode EM field exhibits features very similar to those of a plane wave propagating in free space. Hence the stimulus to which the EUT is subjected in a TEM transmission line is very similar to that present during an ideal radiated immunity test (with the EUT located in the far field of the transmitting antenna).

Through specific test procedures and correlation algorithms, it is also possible to retrieve radiated emission measurements in an Open Area Test Site (OATS) from the emissions measured at the device output due to the EUT radiated emissions.[2]

The fundamental limitation in the original TEM cell design was the frequency range, due to the presence of higher order modes above a cutoff frequency with subsequent field distortion and measurement instabilities. With the use of absorbing material in the termination to reduce the excitation of higher order modes, this limitation has been overcome, changing substantially the way the transmission line is terminated.[3] This development turned TEM cells from double-port devices (having input and output connectors) into wideband single-port devices (with a single input/output connector).

A further evolution has been the improvement of field uniformity in the test region by changing the shape of the septum.[4] Moreover, it has been demonstrated experimentally that replacing the usual continuous metal septum with a longitudinal metal wire array reduces the spurious coupling between the septum and the EUT.[4]

Balanced double-septum TEM transmission line antennas have been introduced by the author for immunity testing up to 200 MHz.[5,6] These antennas exhibit a surprisingly wide uniform test region in comparison with usual unbalanced transmission lines (as in standard TEM or GTEM cells).

A new transmission line device has been recently introduced (Figure 1).[7] The fundamental features of the new device have been already described,[7] and will be reported in the following section. This article compares the cell features to those of other devices, such as the GTEM cell[3] and a 4-wire, balanced transmission line.

In the last section, a number of experimental results on the cell are reported in the frequency range 26 MHz to 3 GHz. The most valuable results are related to the electric field measurements in the frequency range 80 MHz to 1 GHz. These show a good field uniformity level, compliant with the present standards,[8] and cross polarization at reasonably low levels, in agreement with the standards presently under development. [9]

FEATURES

The new cell is a multi-wire, balanced, double-polarization transmission line device with quite a complex structure (Figure 2). The cell is essentially a rectangular cavity including two couples of multi-wire antennas. Each couple is fed in a balanced way, so that if the upper

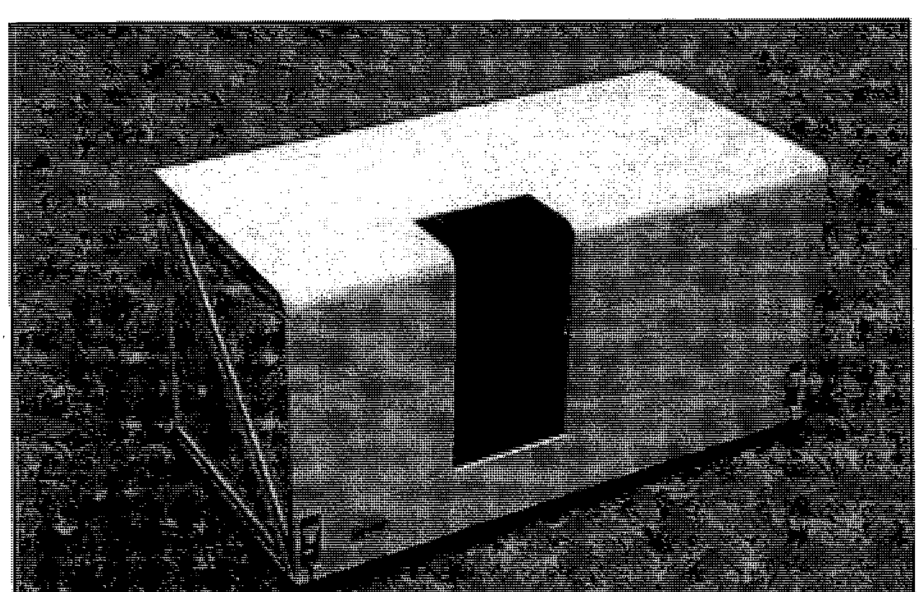


Figure 1. New TEM Cell.

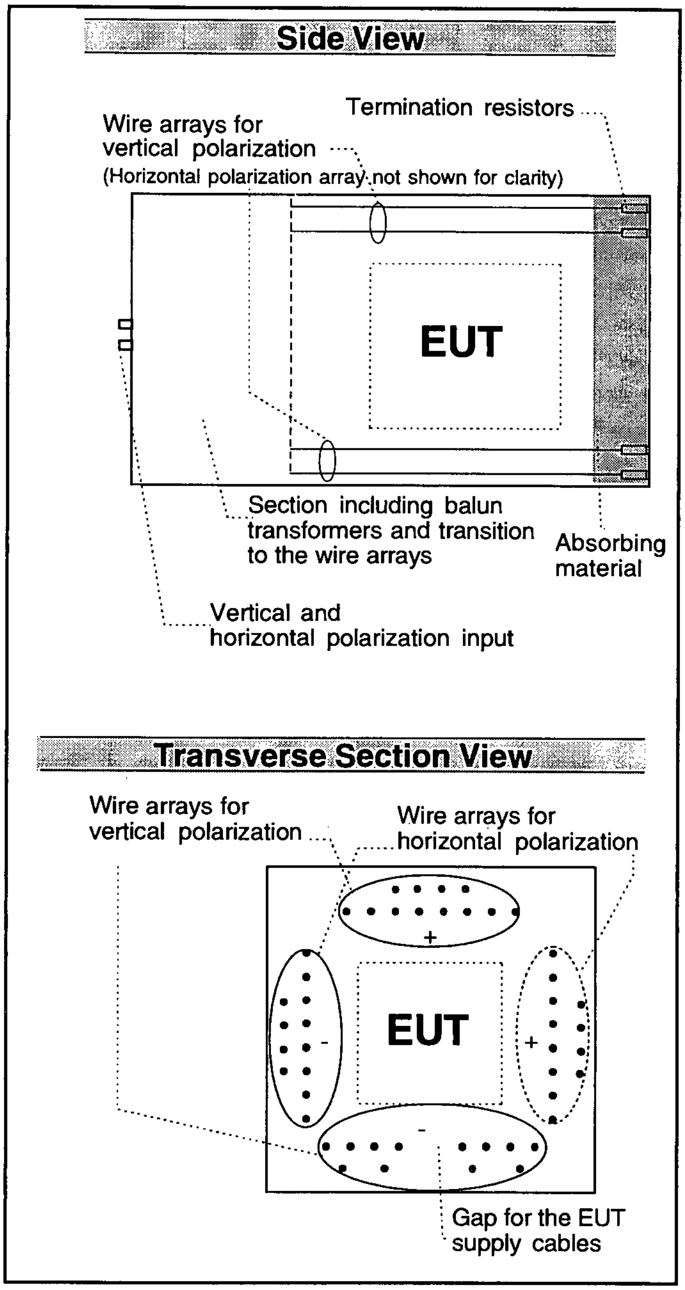


Figure 2. *Scheme of the New TEM Cell.*

and lower antenna are powered, a vertically polarized electric field is available in the test region, while horizontal polarization is generated by the left and right antennas. It should be noted that the lower antenna array is split to allow a region with low field levels for routing cables through the cell floor.

The main advantage of a double-polarization device as compared to a single-polarization device is illustrated (Figure 3). The standards require, both for immunity and emissions testing, a test of the EUT according to two orthogonal linear polarizations (vertical and horizontal). Tests in a single polarization device require a relative rotation between the cell and the EUT, so that the cables interconnecting the EUT with the power supply and/or auxiliary equipment cannot be rotated together with the EUT. This is a serious drawback and a major source of error with respect to free space testing. The EUT and the cables must be considered as a single EM entity because interconnecting cables are usually critical in transmitting and/or receiving RF disturbances. Another obvious advantage is that the EUT does not need to be rotated during the test (switching required of the input connector), so that the cell is particularly well-suited for EUTs with complex external cabling or EUTs which are position-sensitive and which need to operate with a fixed orientation.

One other important feature of the cell is the balanced, double-layer antenna structure. For a good match between the transmission line and the test equipment, a nominal 50-ohm unbalanced input impedance is needed. Since the radiating antennas in the cell are balanced, a balun transformer is needed, converting the 50-ohm input to the physical characteristic impedance of the transmission line antennas. It is possible to guarantee a very wide frequency band for the balun transformer if the output impedance is equal to the input impedance, i.e., 50-ohm balanced. If the impedance is different, transmission line transformers normally exhibit a frequency range limited by the length of the internal windings (a quarter of wavelength) and are difficult to design properly at frequencies exceeding 1 GHz. Unfortunately, a 50-ohm balanced transmission line implies antennas very close to the cell walls. Hence the EM energy is mostly confined between the antenna and the wall rather than in the test region. On the other hand, to increase the field level and to improve the field uniformity, the antennas should move from the cell walls towards the EUT. The solution to this problem is a double-layer structure for the septum (Figure 4). The inner layer generates the field radiating the EUT, while the outer layer (close to the cell wall) trims the impedance of the antenna to 50 ohms.

For the purpose of simulation, a cell with an inner cross section of 0.7 m x 0.7 m is used as a reference. The theory on which the simulation results are based is the same as used in reference 4.

The field level generated inside a (single-polarization) test cell with a nominal input power of 1 watt is shown in Figure 5, while the analogous data for the double layer structure are shown in Figure 6. It can be appreciated that this kind of design leads to a field increase of about 3.5 dB in the test region, i.e., the power necessary to drive the transmission line is 55% lower, a very important savings in the amplifier power when considering the test system to be associated with the test cell.

One other important parameter in a TEM transmission line device is the field uniformity in the test surface, i.e., the electric field variation along the cell cross section. This parameter has a strong influence on the repeatability of the test, and ultimately influences the accuracy of the test level to which the EUT is subjected. The limits described in the standard IEC 1000-4-3 [7] specify a maximum field variation of 6 dB in the test area, at 75% of the grid test points in which the field uniformity is checked.

Figure 7 shows a field uniformity contour plot for the cell in vertical polarization. Figure 8 shows the same result in a horizontal polarization. The value represented in the plots is the ratio of the field in the point to a reference field, i.e., $20^{*}\log_{10}(E/Eref)$, and the dashed contours represent the region in which the field uniformity requirements are met. The reference field level, i.e., the nominal field established in the center of the test region with a 1-watt input power, is 9 V/m. It turns out from the simulations that an EUT with 0.3 m x 0.3 m front face can be tested inside the device, meeting the field uniformity requirements. Hence the EUT-to-cell dimension ratio is fairly favorable for the device, as will be further clarified in the next sections. The test area dimension has been also checked experimentally, as will be shown in the next sections.

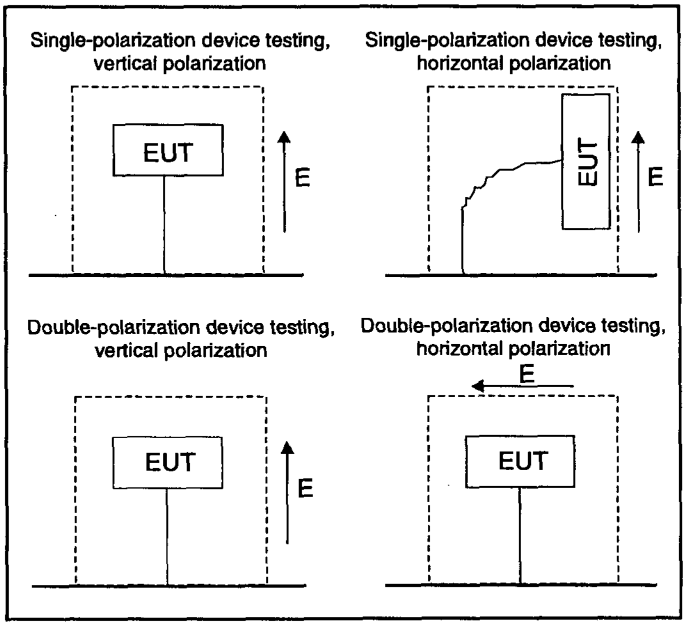


Figure 3. *Advantages of a Double-polarization Device.*

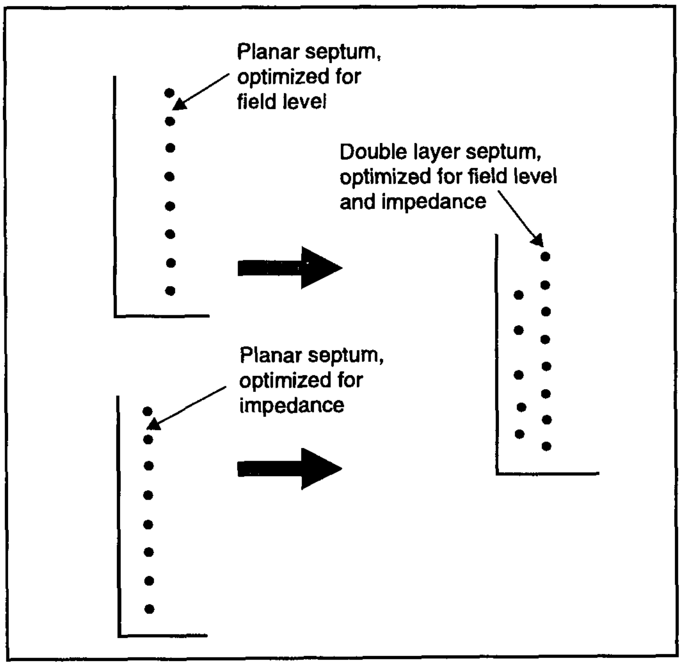


Figure 4. *Septum Design.*

COMPARISON WITH OTHER TEM DEVICES

In this section the difference between the new device and other TEM transmission line devices is discussed. The comparison is based on the simulation of the TEM mode electric field distribution (with the methods described in Reference 10) and should be considered as an indication of the design differences among the different solutions.

The actual differences between the real performance of the different devices depend on the construction details of the structures and the absorbing material quantity and positioning, which influence the excitation and suppression of the higher order modes and subsequent field distortions. These features are not reproduced by the present simulations. Nevertheless, the simulations presented here can be interpreted as fundamental constraints on the performance of the devices, and establish the maximum achievable performance for each different solution.

Two examples are discussed: GTEM-like structures (unbalanced 50-ohm offset strip line in a rectangular waveguide) and a balanced, 4-wire transmission line.

The geometry for the GTEM-like structure is essentially that found in the literature. The exact septum width has been determined in order to obtain a 50-ohm characteristic impedance, and the cell cross section chosen is 1.0 m x 0.7 m (H) for comparison purposes.

The geometry of the 4-wire balanced transmission line has been chosen in order to yield a 50-ohm balanced transmission line, and the wire positions are determined in order to yield a reasonable field uniformity. Minor performance differences can be found in different implementations of this kind of structure, while substantial improvements can be obtained by increasing the characteristic impedance. However, this feature leads to serious difficulties in building a balun transformer with the frequency range extending over 1 GHz (needed to feed the balanced transmission line), as discussed previously.

The electric field distribution in the cell cross section, for a nominal input power of 1 watt, is shown in Figures 9 and 10 for the GTEM-like structure and for the 4-wire line respectively. The region with overall field variation within 6 dB is shown dashed in both cases.

From the viewpoint of field level, in a GTEM-like structure the E-field at 1 watt is about 15 V/m, while in the 4-wire balanced structure the nominal E-field is about 7 V/m. From the viewpoint of field level it is evident that the best result obtainable is through the GTEM. The 4-wire cell exhibits a field level about 2.2 dB lower than the new device (9 V/m), so that the power required for generating a specified field level is about 1.7 times the power required in the cell.

From the viewpoint of field uniformity, the test area in the GTEM-like structure is about 0.52 m x 0.22 m (H) while in the 4-

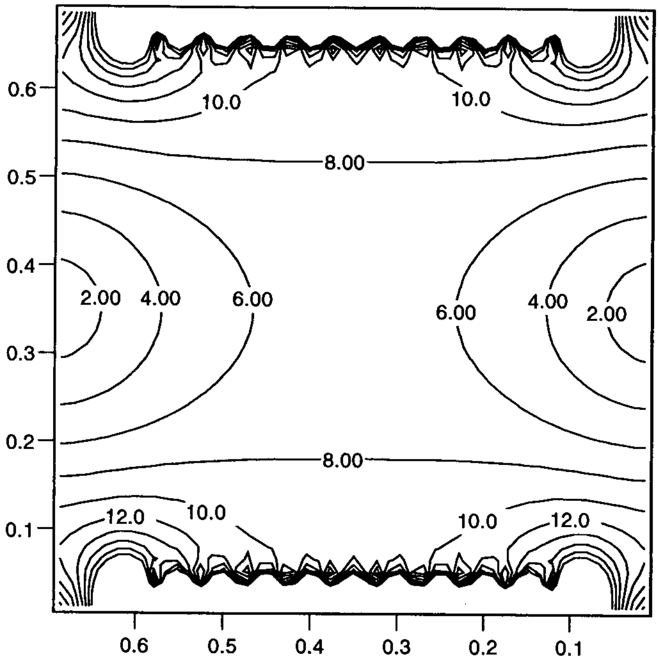


Figure 5. *Electric Field Contour Plot in the Transverse Section of a 50-ohm Planar Balanced Transmission Line with 1-watt Input Power.*

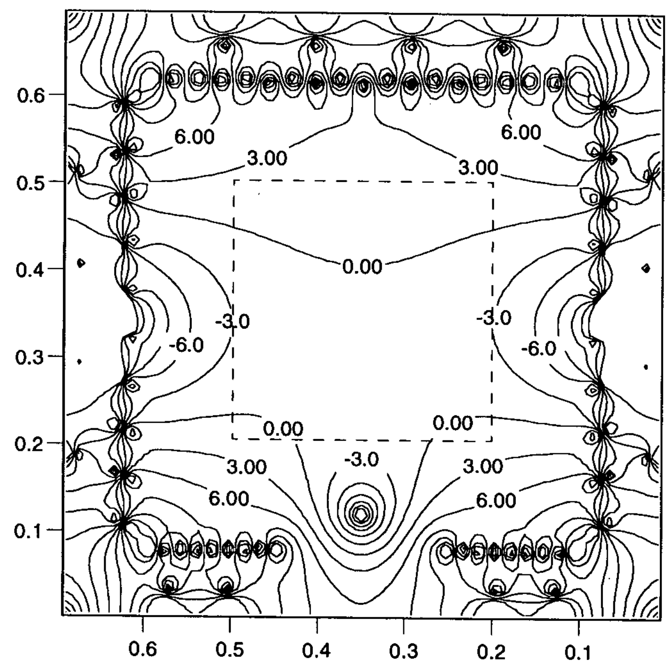


Figure 7. *Field Uniformity (E/Eref[Db]) Contour Plot in the Transverse Section of the Cell, Vertical Polarization.*

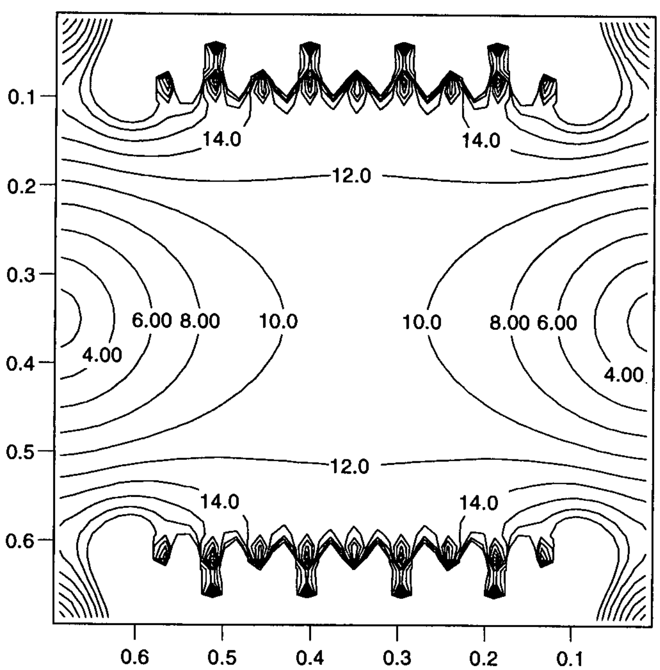


Figure 6. *Electric Field Contour Plot in the Transverse Section of a 50-ohm Double-layer Balanced Transmission Line with 1-watt Input Power.*

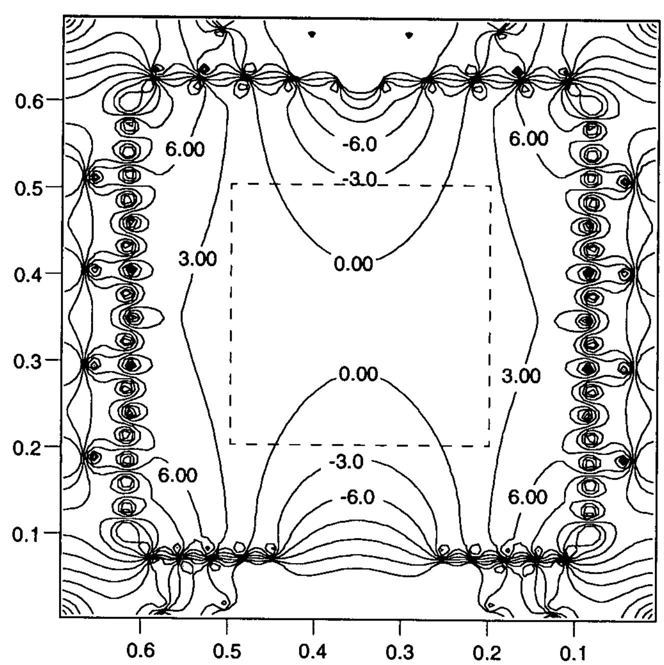


Figure 8. *Field Uniformity (E/Eref[Db]) Contour Plot in the Transverse Section of the Cell, Horizontal Polarization.*

wire cell it is about 0.33 m x 0.33 m (H). The advantage of using balanced transmission lines is quite evident because of the better field uniformity in the test region.

Some final considerations can be drawn regarding the minimum cell cross section dimension necessary to test an EUT with a specified size. Taking as an example an EUT with a square face 0.30 m x 0.30 m, it turns out that:

- A 0.7 m x 0.7 m cross section can be used, with a nominal field value of 9 V/m at 1 watt.
- A 1.36 m x 0.95 m GTEM-like cross section can be used, with a nominal field value of 11 V/m at 1 watt.
- A 0.64 m x 0.64 m 4-wire cross section can be used, with a nominal field value of 7.7 V/m at 1 watt.

Compared to the new device, the GTEM-like structure still allows a power saving of about 43%, at the expense of a structure 94% larger in width and 36% larger in height. (These dimensions are usually even larger because GTEM cells normally exhibit a pyramidal shape.) The 4-wire structure still requires about 1.37 times the power required in the cell, but allows a cross section which is 8 % smaller.

As pointed out at the beginning of this section, the simulated parameters are usually degraded in the practical realization of each design due to field distortion in the presence of the higher order modes. Hence a significant comparison among the performance of the different devices should be based on experimental tests.

EXPERIMENTAL RESULTS

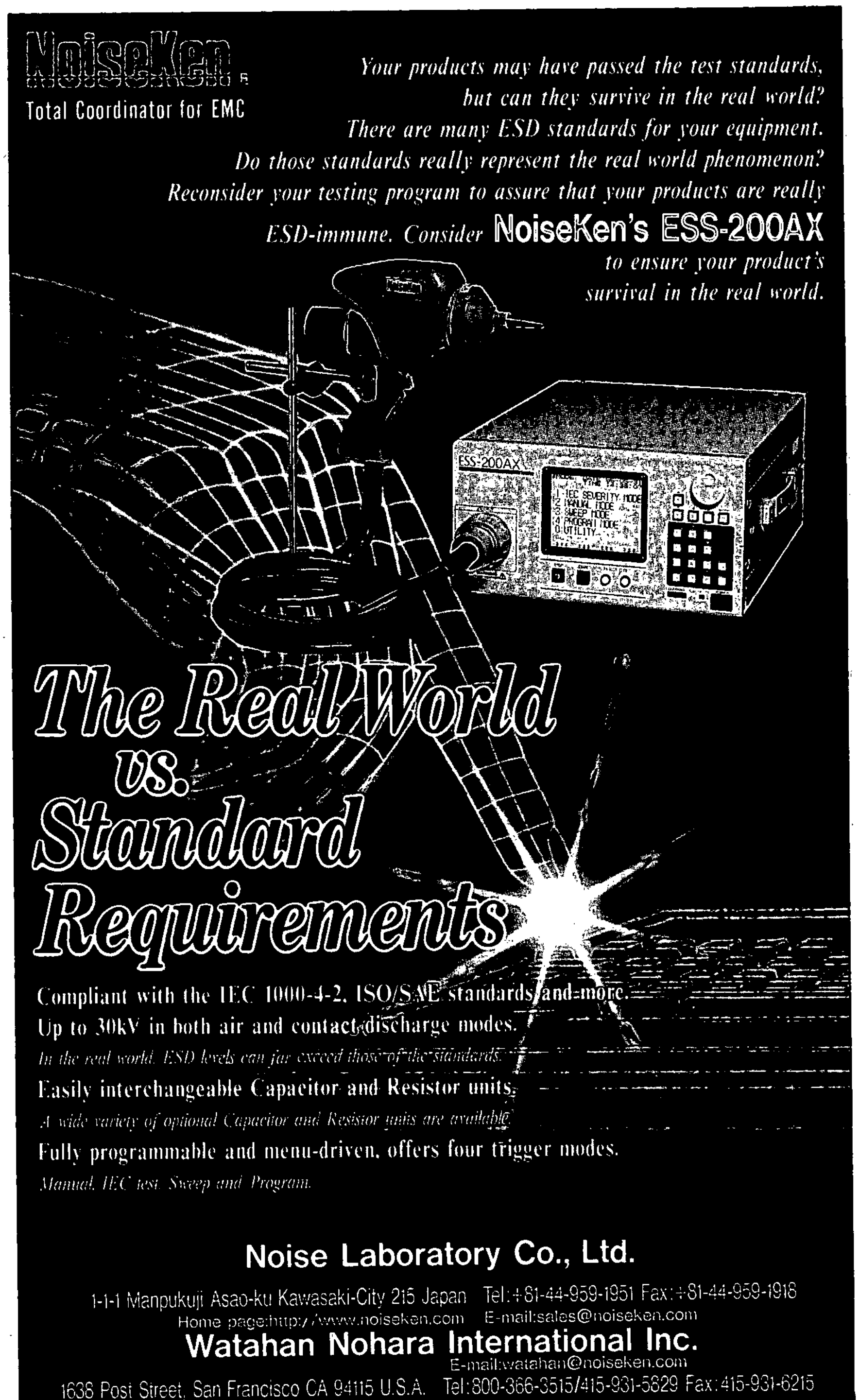
As described in the previous sections, the cell has been designed to perform tests up to 3 GHz. Since a balun transformer is needed to match the balanced lines to the external equipment, the frequency band for the transformer has been constrained to be 26 MHz to 3 GHz. The balun insertion loss in the frequency range 80 MHz to 1 GHz is better than 1 dB.

The measured return loss graph at the balun input (the balun is connected to the cell) is shown in Figure 11. The results which have been found can be summarized as follows:

- Return loss of -8.5 dB (VSWR = 2.2:1) at 26 MHz. This value is due to the low frequency behavior of the balun transformer.
- Return loss better than -12.0 dB (VSWR < 1.65:1) in the band 80 MHz to 1 GHz.
- Return loss better than -9.0 dB (VSWR < 2.1:1) in the band 1 GHz to 3 GHz.

It can be concluded that the frequency range goal of 3 GHz has been substantially met. Field tests are going to be performed to check the field generating performance in the range 1 GHz to 3 GHz.

Electric field tests have been performed in the frequency range 80 MHz to 1 GHz, with 1% frequency steps, in order to check the field uniformity according to the standard IEC 1000-4-3[7] and successive amendments. For the cell size under analysis, the use of a 2 x 2 points test grid would be required according to the standards under development,[8] but for the purpose of a full characterization, a test grid of 3 x 3 points (Figure 12) has been used to span a 0.30 m x 0.30 m test area. The standard requires that at least 75% of the measured field values must be within a tolerance of 6 dB (7 points of 9 in our case) in 75% of the test frequencies. At the remaining 3% of



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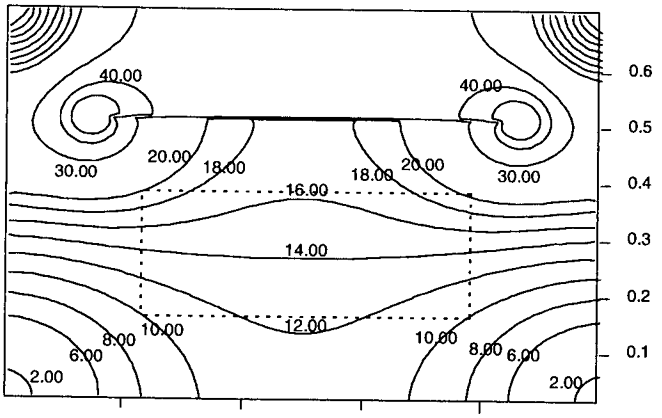

Figure 9. *Electric Field Contour Plot in the Transverse Section of a GTEM-like Cell (Rectangular Shield, Offset Strip Line Septum) with 1-watt Input Power.*

frequencies the limit is relaxed to 10 dB (i.e., 7 frequencies out of 255). The testing has been performed according to the requirements of the last standard updates under discussion,[8] i.e., measuring the desired polarization of the electric field and computing the field uniformity accordingly.

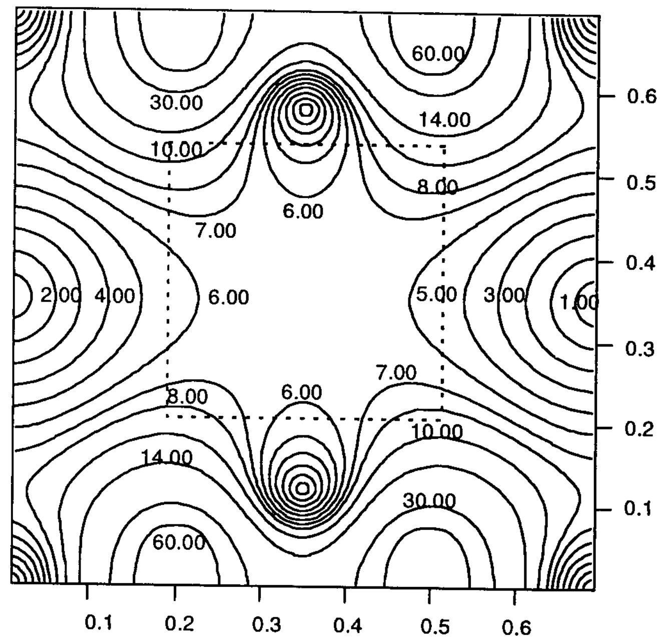

Figure 10. *Electric Field Contour Plot in the Transverse Section of a 4-Wire, Balanced 50-ohm Cell with 1-watt Input Power.*

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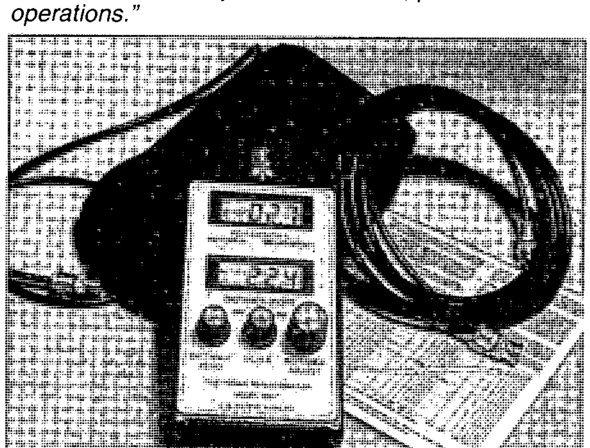

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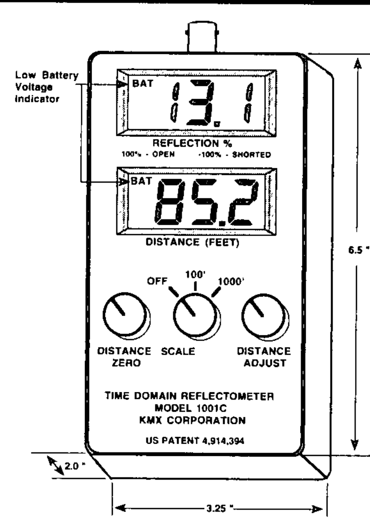

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The results obtained are shown in Figure 13, and are the curves of maximum field deviation for both vertical and horizontal polarization taking into account 7 of 9 points. The results are explained and summarized as follows.

In the range 80 MHz to 400 MHz, the maximum field variation is 5.3 dB for vertical, 5.8 dB for horizontal, considering 100 % of the test points (9 of 9). It should be noted that the cutoff frequency of the first higher mode for the device tested is about 242 MHz; hence the TEM mode field is essentially unperturbed even in the multi-mode region.

In the range 400 MHz to 1 GHz the maximum field variation considering 78% of the test points (7 of 9) is 5.1 dB for vertical polarization, 7.1 for horizontal polarization. For this last case, however, the number of frequencies with field variation exceeding the 6 dB limit is anyway 5 (i.e., 2%), and the field homogeneity requirement is met also for horizontal polarization.

The last test result shown is related to the electric field polarization. The electric field polarization at the center of the test region should be the same as the TEM mode, i.e., vertical or horizontal according to the desired field polarization. On the other hand, higher order TM modes are likely to introduce longitudinal electric field components (in the propagation direction). Hence there is currently some discussion in the regulatory committees in order to decide suitable limits for the cross-polarized components of the electric field.[9]

The ratio between the cross components (horizontal and longitudinal) and the vertical (wanted) electric field component are shown in Figure 14 for the cell, used in vertical polarization mode. The field point is the center of the test region. It can be noted that the cross-polarization level is lower than -6 dB in all but 6 points in the frequency range 80 MHz to 1 GHz (the tests have been performed at 1% frequency steps). At the critical frequencies the cross-polarization level is lower than -2.5 dB.

CONCLUSION

The main features of a device for radiated EMC tests have been shown. The description is based on simulations of the TEM mode electric field distribution and test results. The test results confirm that the device can be used for radiated immunity tests in full compliance with the present standards, and that the frequency range of the device extends up to 3 GHz.

The main feature of the cell is the capability of performing double-polarization tests with good field generation efficiency in a wide test area. To the author's knowledge these two features have been not previously combined in a single device. The performance improvement is mainly due to the double-layer septum structure, that combined with the balanced antenna feature, leads to a wide test area and a reasonably high field level.

A comparison has been performed between the new cell and two other transmission lines (GTEM-like and 4-wire

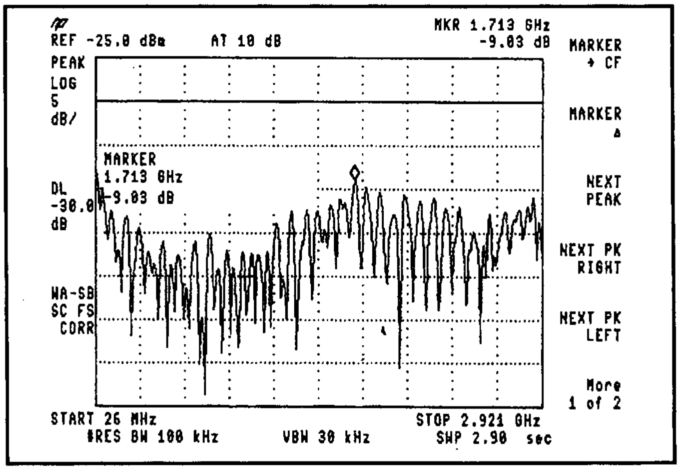

***Figure 11.** Input Return Loss of the Cell, 26 MHz to 3 GHz, Vertical Polarization.*

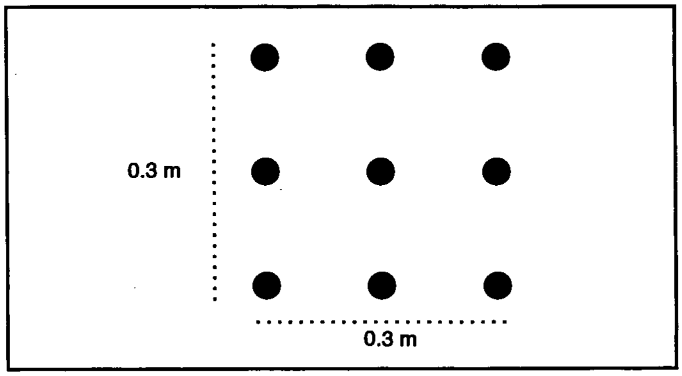

***Figure 12.** 9-point Grid for Electric Field Tests in the Cell.*

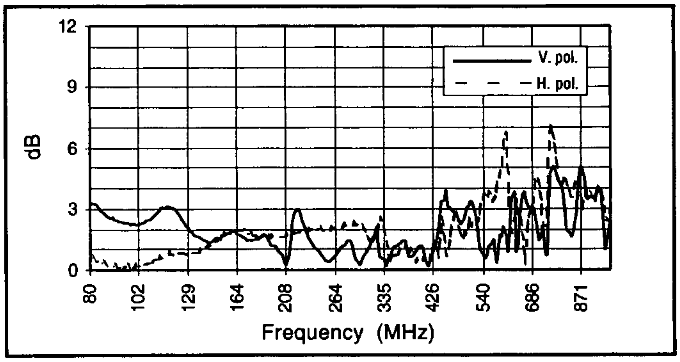

***Figure 13.** Field Uniformity in the Test Cell According to IEC 1000-4-3 and Current Developments, 75% Test Points.*

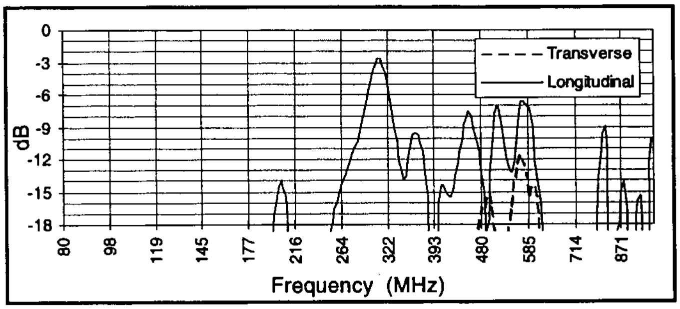

***Figure 14.** Cross -polarization Level in the Test Cell, Center Point, Vertical Polarization.*

balanced line). The advantages and drawbacks of each solution have been discussed.

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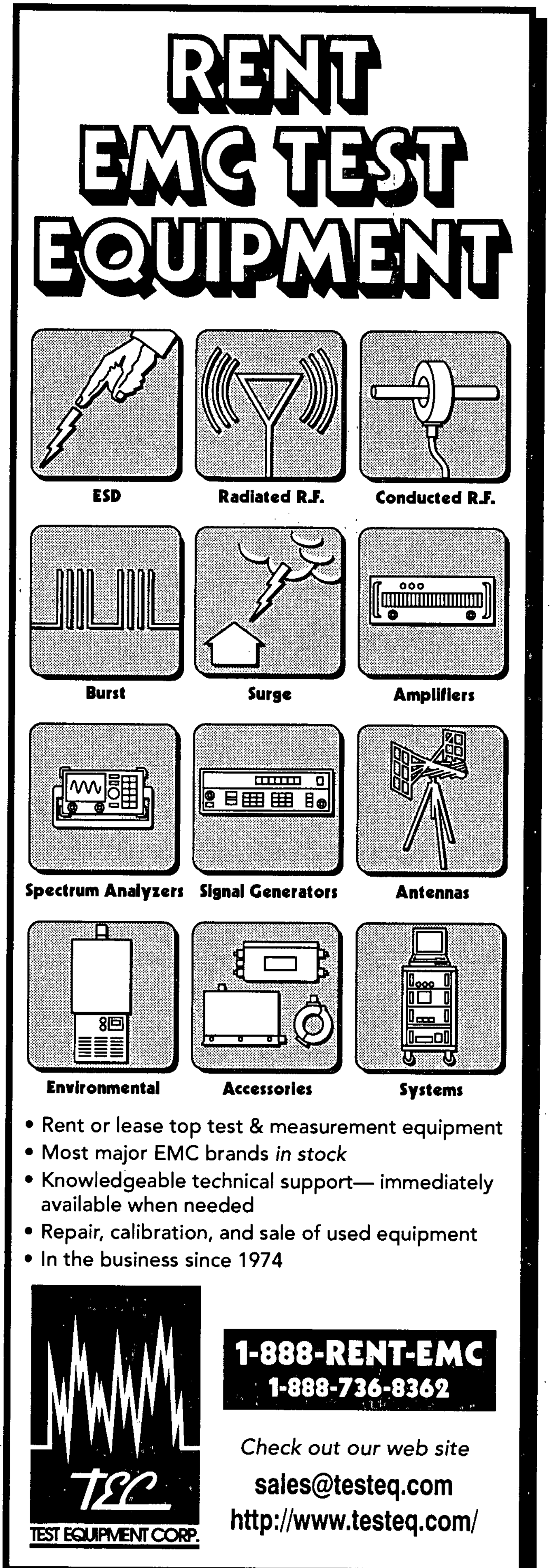

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