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Synthetic TDR Measurements for TEM and GTEM Cell Characterization

Michele Borsero, Giuseppe Vizio, Daniela Parena, and Valeria Teppati

Abstract—**This paper describes the main features of the time-domain reflectometry (TDR) measurement technique and, in particular, the TDR analysis performed using a proper operating mode of the vector network analyzer (VNA), which is called synthetic TDR. Furthermore, some results of reflection measurement, which aim to characterize the impedance behavior of transverse electromagnetic (TEM) and *gigahertz* TEM cells by means of a commercial VNA in time-domain mode, are presented.**

Index Terms—**Gigahertz transverse electromagnetic (GTEM), impedance, reflection coefficient, time-domain reflectometry (TDR), transverse electromagnetic (TEM), vector network analyzer (VNA), VNA measurements.**

I. INTRODUCTION

TIME-DOMAIN reflectometry (TDR) provides a very useful technique to localize and characterize the reflection that a signal undergoes along a transmission line. In Fig. 1, a common TDR device is sketched: Using a step generator and sampling the reflected waveform with an oscilloscope, it is possible to know the impedance of simple discontinuities and identify its type (resistive, inductive, or capacitive) [1], [2].

By means of a step (or pulse) generator, a progressive incident wave is sent to the device under test and travels along the transmission line with its own propagation velocity.

If the load impedance is equal to the characteristic impedance of the line (perfect match), no reflected wave is generated, and only the step of the incident voltage is observed on the oscilloscope. On the contrary, if there is a load mismatch, part of the incident wave is reflected back and displayed on the oscilloscope, algebraically summed to the incident one, with a certain delay.

Conventional TDR, which is very useful for qualitative investigations, has some limits that affect its accuracy, but with the large diffusion of vector network analyzer (VNA) and of digital signal processing (DSP), the reflection coefficient versus time can be obtained with the inverse Fourier transform of the network reflection coefficient, which is measured by a VNA in frequency domain. This technique, which is called synthetic TDR, is implemented almost in all VNAs and used in several different fields.

With respect to the conventional TDR, the use of data acquired in frequency domain and then elaborated with mathematical methods [3] provides several advantages, particularly the precise knowledge of pulse or step waveform and of the equivalent bandwidth, the availability of vector data corrected for systematic effects, the removal of spurious reflections, and a large dynamic range.

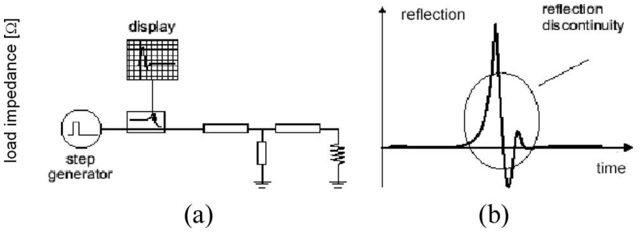

Fig. 1. (a) TDR system based on a sampling scope and pulse generator, with an example of load scheme. (b) Typical impulsive response in time domain.

II. TRANSVERSE ELECTROMAGNETIC (TEM) AND GIGAHERTZ TEM (GTEM) CELL CHARACTERIZATION WITH SYNTHETIC TDR

TDR analysis can be performed using a proper operating mode of the VNA, where the DSP system allows to directly implement the fast Fourier transform algorithm [4].

Time-domain mode in the VNA offers the possibility to choose

- the processing method (low-pass or bandpass);
- the *windowing* to be applied to the data in frequency domain to overcome the problems due to the finite definition interval of the Fourier transform and to attenuate the edge effects [5];
- the *gating*, acting as a filter in time domain.

The TEM cell used for the measurements [see Fig. 2(a)] is a large coaxial line with characteristic impedance of 50 Ω, by means of which it is possible to produce a uniform reference electromagnetic field propagating in TEM mode, for frequencies from about 10 kHz to 200 MHz. For frequencies between 100 MHz and 4 GHz, the GTEM cell is used [Fig. 2(b)], which can be considered a hybrid of a TEM cell and an anechoic chamber.

TEM and GTEM cell characterization is performed mainly by means of the frequency response analysis, the evaluation of the field uniformity inside the test volume, and the measurement of the reflection coefficient Γ in the working frequency range of the cell. Through the measurement of the Γ coefficient at the input port, the cell's impedance behavior can be studied. This kind of measurement can be performed by means of a true TDR system or with a VNA (synthetic TDR) [6], [7]. On the

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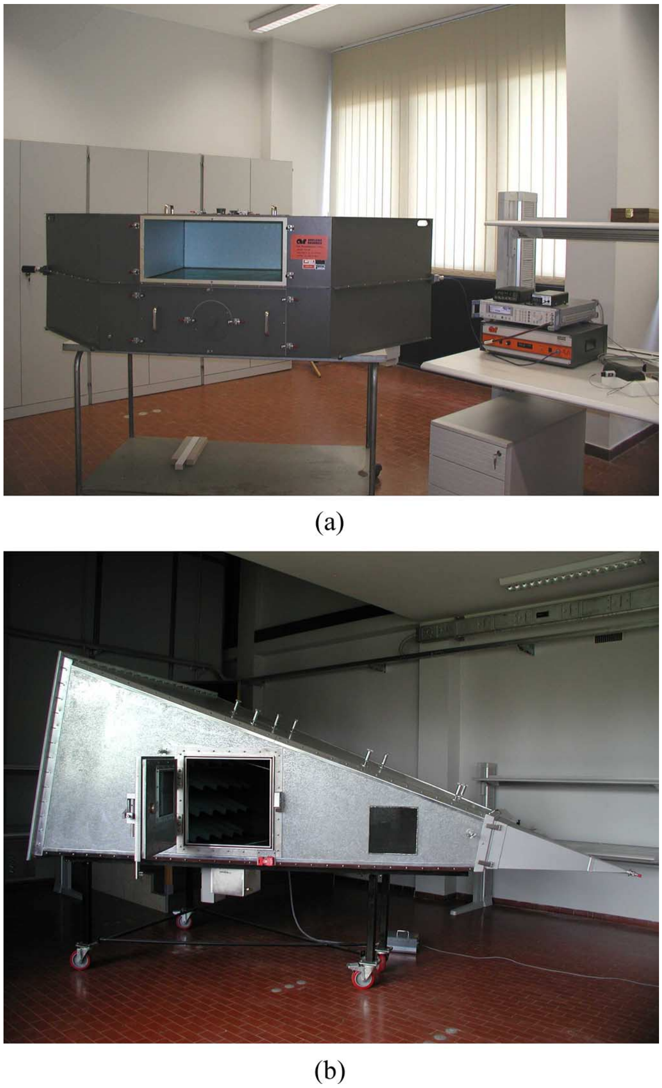
(a)

(b)

Fig. 2. (a) TEM cell. (b) GTEM cell.

other hand, the evaluation of the field uniformity inside the cell requires the analysis of the effects due to the discontinuities of the cell geometry. This aspect is particularly important for the GTEM cell, which has a more complex structure than the traditional TEM cell, and for this purpose, the TDR measurements can be very useful.

Measurements on the cells with synthetic TDR have been performed with a three-channel bidirectional VNA, with a frequency band from 9 kHz to 4 GHz, preliminarily calibrated for systematic error correction [1]. Conversion from frequency-domain to time-domain data has been performed by the chirp z-transform algorithm [8], and the Hann window [5] has been applied to the data. The VNA can operate in low-pass or bandpass mode [6]: Since the GTEM cell has a large bandwidth, for this device, the low-pass procedure, which is more powerful and accurate, is preferable. For the TEM cell, although the limited bandwidth could suggest the use of bandpass mode, the measurements have been performed in low-pass mode in order to identify the type of discontinuity and to have results comparable with the GTEM ones.

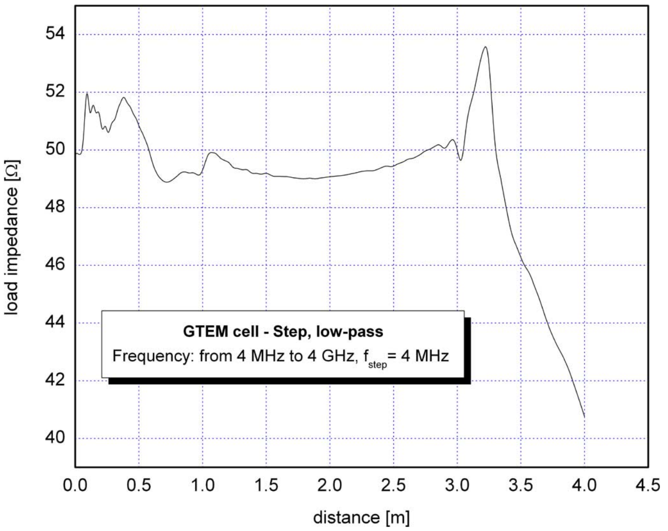

Fig. 3. TDR measurement with VNA: empty GTEM cell impedance, low-pass step mode.

III. MEASUREMENT RESULTS

In the following, results of reflection measurements performed on the GTEM and TEM cells are presented in terms of S_{11} parameter (the scattering parameter related to the reflection coefficient) or load impedance versus distance along the cell longitudinal axis, where the space is related to the time through the signal propagation velocity.

The plot in Fig. 3 shows the step response obtained in low-pass mode from a GTEM cell. In the first part of the cell, for about 1 m, there is a considerable deviation of the impedance from the nominal value of 50 Ω: Values up to about 52 Ω have been measured, due to discontinuities produced by the connector matching the standard coaxial cable to the instrument and by the cell's apex, which is a separate metallic block.

In the central part of the cell, the impedance is fairly constant, with values lower than 50 Ω, whereas at distances greater than 3 m from the cell apex, considerable variations of the impedance values are observed: Two small capacitive discontinuities [4] correspond to the tips of the pyramidal absorbers (the distributed load), whereas the peak at about 3.2 m (inductive type) is related to the resistors, which are placed among the absorbers and work as a lumped load.

In Fig. 4, the response of the GTEM cell to the pulse signal is shown in terms of S_{11} parameter, which is obtained again in low-pass mode: The position of the discontinuities produced in the last part of the cell can be observed more clearly.

The measurement of impedance along the cell has been performed also for the TEM cell, with the same instrumentation and procedures used for the GTEM cell. In the case of TEM cell, due to the narrow bandwidth for correct operation of this device, the VNA in time-domain mode cannot provide accurate results for intrinsic limits of the instrument.

Anyway, the working bandwidth from 4 MHz to 4 GHz has been chosen, approximately corresponding to the VNA operating bandwidth, because the request of compatibility with the cell's bandwidth (nominally from direct current up to 375 MHz) would give rise to an insufficient spatial resolution (approximately given in millimeter by 150/frequency span in gigahertz).

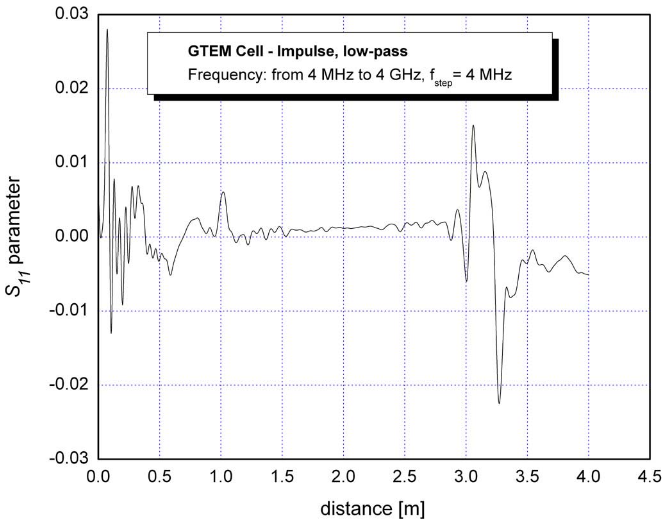

Fig. 4. TDR measurement with VNA: empty GTEM cell S_{11} parameter, low-pass impulse mode.

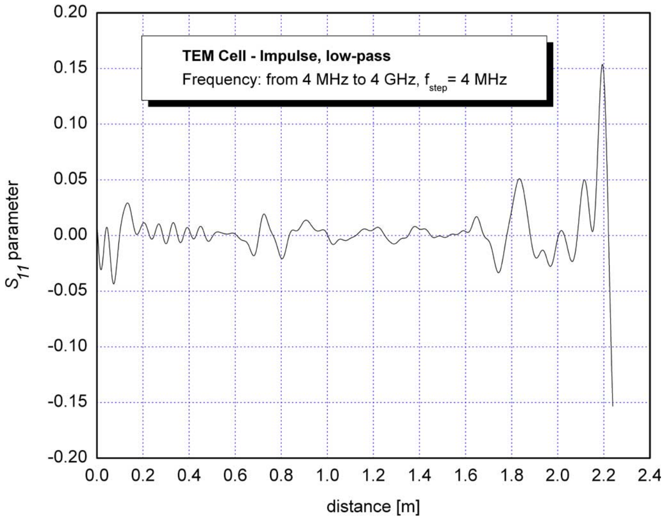

Fig. 6. TDR measurement with VNA: empty TEM cell S_{11} parameter, low-pass impulse mode.

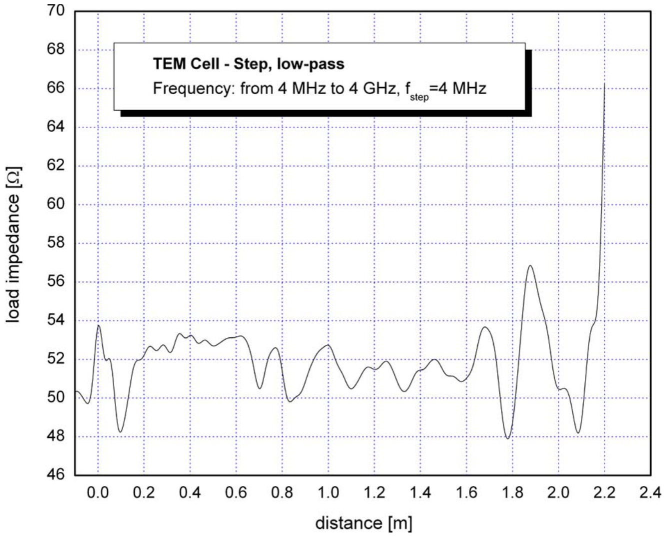

Fig. 5. TDR measurement with VNA: empty TEM cell impedance, low-pass step mode.

Figs. 5 and 6 show the impedance behavior versus the distance along the cell, which is obtained in low-pass mode, as step and pulse response, respectively. Again, in the central section of the TEM cell (about 1–1.4 m), the impedance variations are sufficiently small, between 50 and 52 Ω, and the reflection coefficient is close to zero.

The TEM and GTEM cells are used at the Istituto Nazionale di Ricerca Metrologica (INRIM) to generate reference electromagnetic fields for calibration purposes. As known, the uncertainty associated with the field-strength value in the test volume of the cell is a combination of different uncertainty contributions, according to the model equation presented in a previous work [9].

As an example, the uncertainty budget of the TEM cell presently used at INRIM is shown in Table I, where the following contributions are considered:

- u_P is the uncertainty due to the net power measurement at the cell input port;
- u_Z is the uncertainty on the value of characteristic impedance of the cell;
- u_b is the uncertainty on the value of the distance between the septum, which is the metallic plane replacing the internal wire of a conventional coaxial cable, and the upper (or lower) wall of the cell;
- u_D is the uncertainty due to field non-uniformity in the test volume of the cell.

In this budget, the uncertainty u_Z related to the cell impedance was evaluated mainly through previous S_{11} measurements at the input port of the cell, and a value of 8.5%, with a rectangular probability distribution, was estimated. This value represents the maximum deviation of the impedance from its nominal value of 50 Ω used in the reference field calculation.

The results obtained in this paper through the synthetic TDR investigation on the TEM cell (Figs. 5 and 6) seem to lead to better impedance values in the sections of interest (deviations from the nominal value within 5%). Therefore, they not only confirm the values previously estimated but also reduce the u_Z uncertainty contribution.

Similar considerations on the cell impedance and related uncertainty can be done also in the case of the GTEM measurements.

IV. CONCLUSION

Some measurement results obtained with synthetic TDR have been presented, which are aimed to characterize TEM and GTEM cells by measuring the S_{11} parameter, in order to evaluate the impedance of the device versus the position along the longitudinal axis.

The synthetic TDR offers a more accurate impedance evaluation inside the volume in which the reference field is generated. The obtained results are promising and could be used to reduce the uncertainty related to the cell impedance and, consequently, that of the reference field value. Nevertheless, to this purpose, a deeper analysis and estimate of the different uncertainty contributions are required, taking into account not only the intrinsic

TABLE I
UNCERTAINTY OF THE REFERENCE FIELD IN A TEM CELL

Uncertainty component	Probability distribution	Standard uncertainty	Sensitivity coefficient	Contribution to the combined uncertainty
u_P	Normal	2.4 %	½	1.2 %
u_Z	Rectangular	5 %	½	2.5 %
u_b	Rectangular	1 %	1	1 %
u_D	Rectangular	4 %	1	4 %
u	Normal	-	-	5 %
$U(k=2)$	Normal	-	-	10 %

uncertainty of the VNA calibration but also the uncertainty related to the transformation and filtering procedures. These items are the subject of a future development of the work, together with a systematic comparison between synthetic and conventional TDR applied to this kind of devices.

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