Analysis of Probe-coupled Cylindrical Microwave Cavity with Plan Parallel and Dielectric Layers

Tijana Dimitrijevic, Jugoslav Jokovic and Bratislav Milovanovic
University of Nis, Faculty of Electronic Engineering
Aleksandra Medvedeva 14
Nis 18000, Serbia
{tijana, jugoslavbata}@elfak.ni.ac.rs

ABSTRACT: *The probe-coupled cylindrical microwave cavity with plan parallel and dielectric layers is analyzed. We discuss testing a compact wire model used in the 3D TLM cylindrical mesh for analysing the dielectric layers. The wire structures parameter measures help the implementation of the compact wire model. The conditions include the cross-section variables of the TLM nodes where the wire conductor passes in the cylindrical grid with a wire path. Implementing the compact wire model into a cylindrical TLM mesh is based on the calculation of wire structure parameters. The results are obtained and compared with plan parallel dielectric permittivity studies. For testing the TLM-based approach for characterization of a cylindrical metallic cavity loaded.*

Keywords: Cavity Resonators, Electromagnetic Analysis, Dielectric Layer, Probe Antennas, Wire Model, Cylindrical Grid

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1. Introduction

Extensive use of microwave energy in communication, industry, science and medicine has led to the development of a number of different microwave devices based on microwave metallic cavities [1-3]. Among them, the most popular ones are resonant applicators classified as either single or multimode cylindrical metallic cavities, partially loaded with dielectric slabs, widely used in the processes of material heating and drying. They come in various shapes and sizes based on the electromagnetic (EM) properties, geometry and volume of dielectric materials. The knowledge of the mode tuning behavior in a cavity under loading condition (i.e. physical and electrical parameters of the load) forms an integral part of the studies in microwave heating and can significantly help in designing these applicators.

Electromagnetically-based numerical TLM (Transmission- Line Matrix) time-domain method can be successfully used to investigate an influence of different EM and geometric parameters of dielectric materials used as a load in microwave cavity applicators on cavity's resonant frequencies [4-7].

Desired mode distribution in the modelled cavity can be established exciting a particular field component through an impulse excitation. However, this way of setting up the wanted TE or TM mode obviously differs from the experimental procedure [7] where a probe, placed inside a cavity, is used as an excitation. Consequently, numerical results obtained in case of an impulse excitation would be different from the experimental ones, in terms of resonant frequency values and an EM field level. Further, since the reflection and transmission characteristics are common parameters in the cavity exploration, input and output ports of real microwave cavity devices are generally realized by coaxial probe that ensures coupling with corresponding electromagnetic (EM) field component [1]. For that reason, physical and electrical probe parameters form an integral part of microwave technique studies regarding EMC (electromagnetic compatibility) problem of a probe-coupled cavity.

The TLM enhancement in form of the compact model for wire structures has been developed [8, 9], yielding a significant improvement in the required computer resources compared to the traditional TLM method. The so-called TLM wire node has been implemented into the uniform TLM mesh based on a rectangular grid, as mean cross-section dimensions of nodes through which a wire conductor runs are always constant, allowing to easily preserve distributed capacitance and inductance of a wire per unit length. However, if a rectangular uniform mesh is used to model a cylindrical structure [10, 11], a curved boundary would have to be described in a step-wise fashion which might result in a deviation of resonant frequency values as well as in excitation of unwanted modes. A numerical error could be reduced by applying the TLM mesh of a higher resolution, which would result in increasing the simulation time. Moreover, a mesh resolution increasing is limited since an implementation of the compact wire model into the rest of the TLM mesh is based on arbitrary ratio between radius of a wire and dimensions of nodes through which a wire conductor passes. Consequently, a higher resolution of an applied rectangular TLM mesh enables a cylindrical cavity to be precisely modelled only if probes of a relatively small radius are used [10, 11].

These limitations of the rectangular TLM mesh for the purpose of the modelling of a probe-coupled cylindrical cavity were overcome by implementation of the TLM wire node into the cylindrical TLM grid. This solution has enabled the precise modelling of cylindrical cavity boundaries independently of a mesh resolution applied. However, in case of probes that are radially placed, mean cross-section dimensions of cylindrical TLM nodes along the wire path are variable from one node to another, leading to different wire network properties between nodes. For that reason, an additional connecting procedure for wire segments belonging to TLM nodes with different cross-sections has been implemented [12].

In this paper, an efficiency of the TLM wire model adapted to cylindrical mesh has been verified on the example of a probe-coupled cylindrical metallic cavity loaded with planparallel dielectric layer placed at the arbitrary height from a cavity bottom. The transmission coefficient based on the coupling of two wire probes inserted into the cavity has been considered numerically and experimentally.

2. Modeling Procedure

In the conventional TLM time-domain method, an EM field strength in three dimensions, for a specified mode of oscillation in a metallic cavity, is modelled by filling the field space with a network of link lines and exciting a particular field component through incident voltage pulses on appropriate lines. An efficient computational algorithm of scattering properties, based on enforcing continuity of the electric and magnetic fields and conservation of charge and magnetic flux [13], is implemented to speed up the simulation process. EM properties of different mediums in the cavity are modelled by using a network of interconnected nodes, a typical structure known as the symmetrical condensed node – SCN [13]. Each node describes a portion of the medium shaped like a cubic (Cartesian rectangular mesh) or a slice (Non-Cartesian cylindrical mesh) depending on the coordinate system applied. Additional stubs may be incorporated into the TLM network to account for inhomogeneous materials and/or electric and magnetic losses.

When cylindrical structures are concerned, a non-Cartesian cylindrical mesh in the coordinate system (f, r, z) can be used for the modelling purpose. The coordinate system used and the port designations are shown in Fig. 1. Simulation proceeds exactly as for a SCN with stubs in a Cartesian grid. The only modification involves the calculation of stub parameters where account must be taken of the details of the new geometry.

The TLM wire node in a cylindrical grid is based on a SCN with one small modification in the form of additional link and stub lines interposed over the existing network to account for increase of capacitance and inductance of the medium caused by wire presence. The single column of TLM nodes, through which a wire conductor passes, can be used to approximately form the fictitious cylinder which represents capacitance and inductance of a wire per unit length [8].

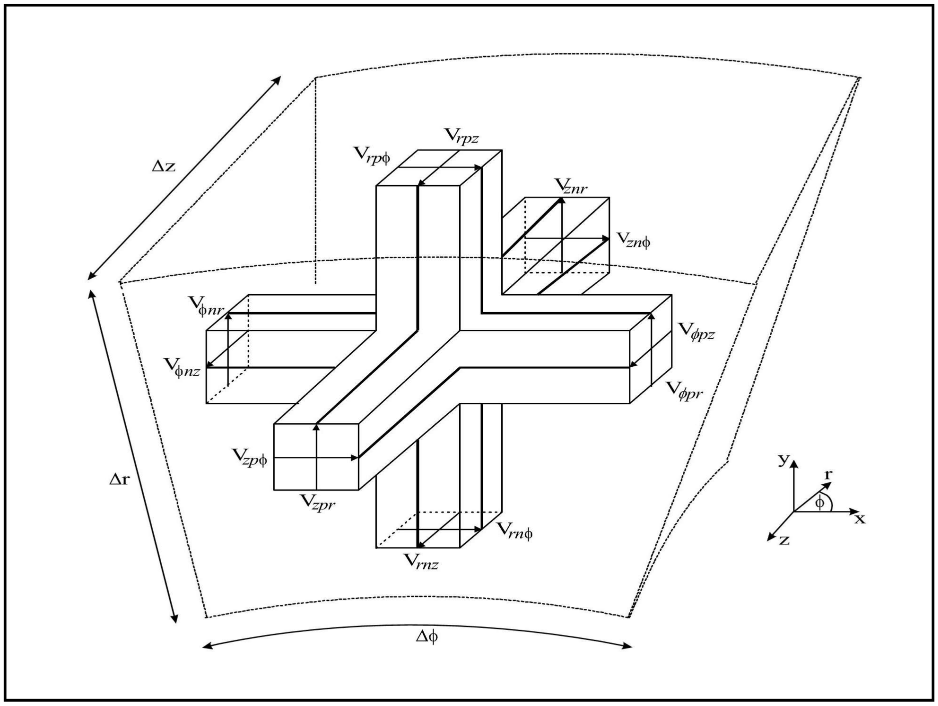


Figure 1. A cylindrical SCN

An equivalent radius of the fictive cylindre in a cylindrical grid for calculating the capacitance and inductance, r_{Cr} and r_{Lr}, respectively, for a wire segment running along radial direction are $r_{Cr} = k_{Cr}\Delta r_c$ and $r_{Lr} = k_{Lr}\Delta r_c$, where Δr_c represents a mean dimension of the node cross-section in r direction ($\Delta r_c = \left(\frac{(r_i + r_{i+1})}{2}\Delta\varphi + \Delta z\right)/2$, (where r_i and r_{i+1} are lower and upper limits of the TLM wire node in radial direction (Figure 3)), while r_{Cr} and r_{Lr} are factors empirically obtained by using known characteristics of the TLM network.

Distributed capacitance and inductance per unit length, needed for modelling of wire segments, may be expressed as:

$$C_{wr} = \frac{2\pi\varepsilon}{\ln(r_{Cr}/r_w)}, \ L_{wr} = \frac{\mu}{2\pi}\ln(r_{Lr}/r_w) \qquad (6)$$

where r_w is a real probe radius.

An equivalent radius of the fictitious cylinder can be easily kept constant along nodes column in a rectangular grid.

However, for a radial wire conductor in a cylindrical grid, as it is shown in Fig. 3, mean cross-section dimensions of TLM nodes, through which a wire passes, vary making difficult to preserve distributed capacitance and inductance of a wire per unit length. As result, admittance of the wire network link line, interposed over the existing network to account for wire presence, varies from one TLM node to another (Figure 2).

Therefore, an additional connecting procedure for wire segments with different link-lines admitances has been implemented into the existing TLM-based software [12].

Reflected voltages on both directions of the interface between nodes with different cross-section, which at the same time represent incident voltages respect to the node center for the next time step, can be expressed as follows:

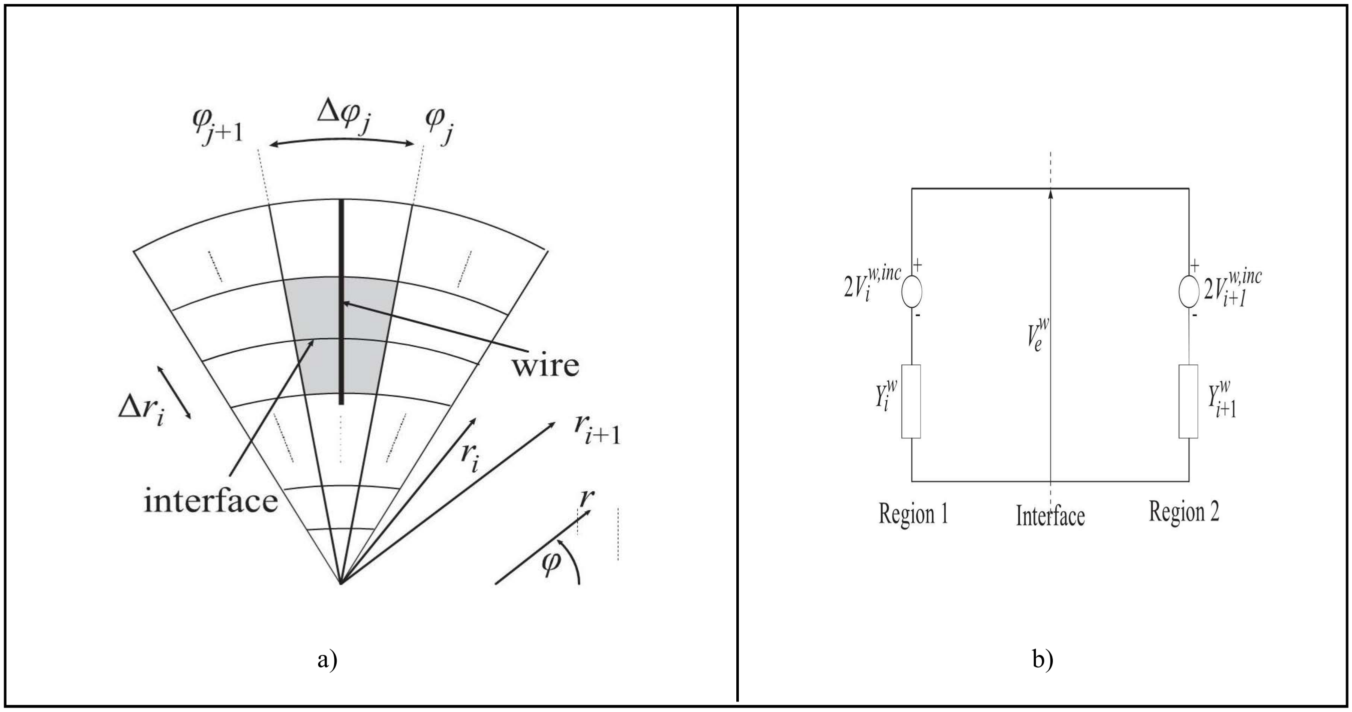


Figure 2. a) TLM nodes in $r\phi$ plane through which wire runs and b) an interface between two nodes

$$V_e^w = 2V_{i+1}^{w,inc}\frac{Y_{i+1}^w}{Y_i^w + Y_{i+1}^w} + 2V_i^{w,inc}\frac{Y_i^w}{Y_i^w + Y_{i+1}^w} \quad (7)$$

$$V_i^{w,ref} = \frac{Y_i^w - Y_{i+1}^w}{Y_i^w + Y_{i+1}^w}\left(V_i^{w,inc} - V_{i+1}^{w,inc}\right) + V_{i+1}^{w,inc} \quad (8)$$

$$V_{i+1}^{w,ref} = \frac{Y_i^w - Y_{i+1}^w}{Y_i^w + Y_{i+1}^w}\left(V_i^{w,inc} - V_{i+1}^{w,inc}\right) + V_i^{w,inc} \quad (9)$$

where $V^w{}_e$ is an equivalent voltage at the interface, $V_i^{w,inc}$, and $V_{i+1}^{w,inc}$ are the incident voltages.

Such compact wire model allows for simple incorporation of voltage/current sources and lumped loads and takes into account the physical dimensions of wire probes [9], determined only by TLM mesh resolution.

When modelling of cavities containing lossy loads is concerned, implementation of losses in the TLM model is carried out by introduction of stubs with losses in the nodes where scattering is going on. Stubs with losses may be considered as infinitely long transmission lines, or equivalently, as lines terminated with its characteristic impedance. They can be used to model either electric or magnetic losses. In case of the symmetrical condensed node, stubs with losses are directly implemented in the scattering procedure, includinmg coupling with the corrsponding EM field component.

If σ_{ek} and σ_{mk} represent effective electric and magnetic conductance, respectively, in k-direction, where $k = (\varphi, r, z)$, elements in the TLM node used for modelling of losses are defined as:

$$G_{ek} = \sigma_{ek} \frac{\Delta i \Delta j}{\Delta k}, \; R_{mk} = \sigma_{mk} \frac{\Delta i \Delta j}{\Delta k} \quad (10)$$

where $(\Delta i, \Delta j, \Delta k) = (r\Delta\varphi, \Delta r, \Delta z)$.

Starting from $\varepsilon_k^* = \varepsilon_o \varepsilon_{rk} - j\frac{\sigma_{ek}}{\omega}$, $\mu_k^* = \mu_{rk} - j\frac{\sigma_{mk}}{\omega}$ [13], it is possible to define a loss tangent at the appropriate frequency as:

$$\tan\delta_{ek} = \frac{\sigma_{ek}}{2\pi f \varepsilon_0 \varepsilon_{rk}}, \; \tan\delta_{mk} = \frac{\sigma_{mk}}{2\pi f \mu_0 \mu_{rk}} \quad (11)$$

Finally, corresponding equations for reflected total voltages and currents in corresponding direction have to be modified in case of modelling of mediums with losses [13].

3. Results and Analyses

The proposed TLM model based on the cylindrical grid and enhanced with the TLM wire node has been used for modelling of a loaded probe-coupled cylindrical cavity with dimensions a = 7 cm and h = 14.24 cm, chosen to follow the experimental ones [7]. Wire probes, representing a feed and receiving probe, were placed at the height l = 7.4 cm from the bottom of the cavity, along the radial direction and opposite to each other (Figure 3). In order to model real coaxial cable characteristics, the probes were connected, through the TLM wire port, to the real voltage source and resistances of 50Ω. In order to illustrate effect of probe length changing to EM field distribution, analyses have been carried out for different length of probes $d_1 = d_2 = d$ = 4 and 5 cm, respectively.

Two types of the loaded cavity have been considered. One represents the cavity containing only one layer of water placed at h_1 = 10cm from the bottom of the cavity (Figure 3a), whereas the other contains two water layers, one at the bottom and the other at h_1=10cm from the cavity bottom, (Figure 3b). The height of the each layer is h_2 = 3cm. The permittivity of the water was taken

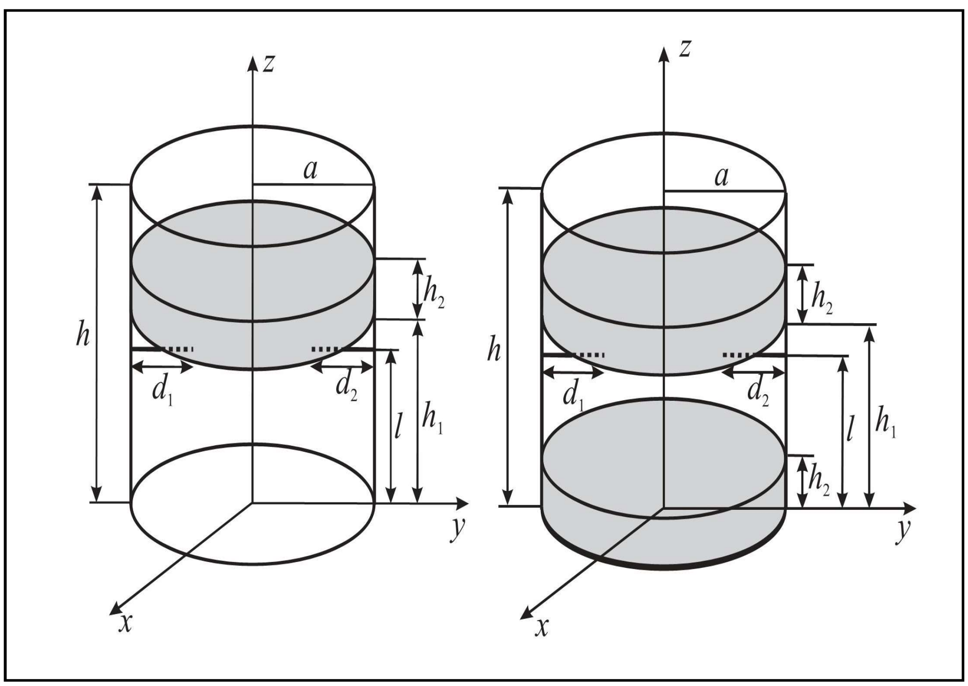


Figure 3. A probe-coupled loaded cylindrical cavity with a) one water layer and b) two water layers

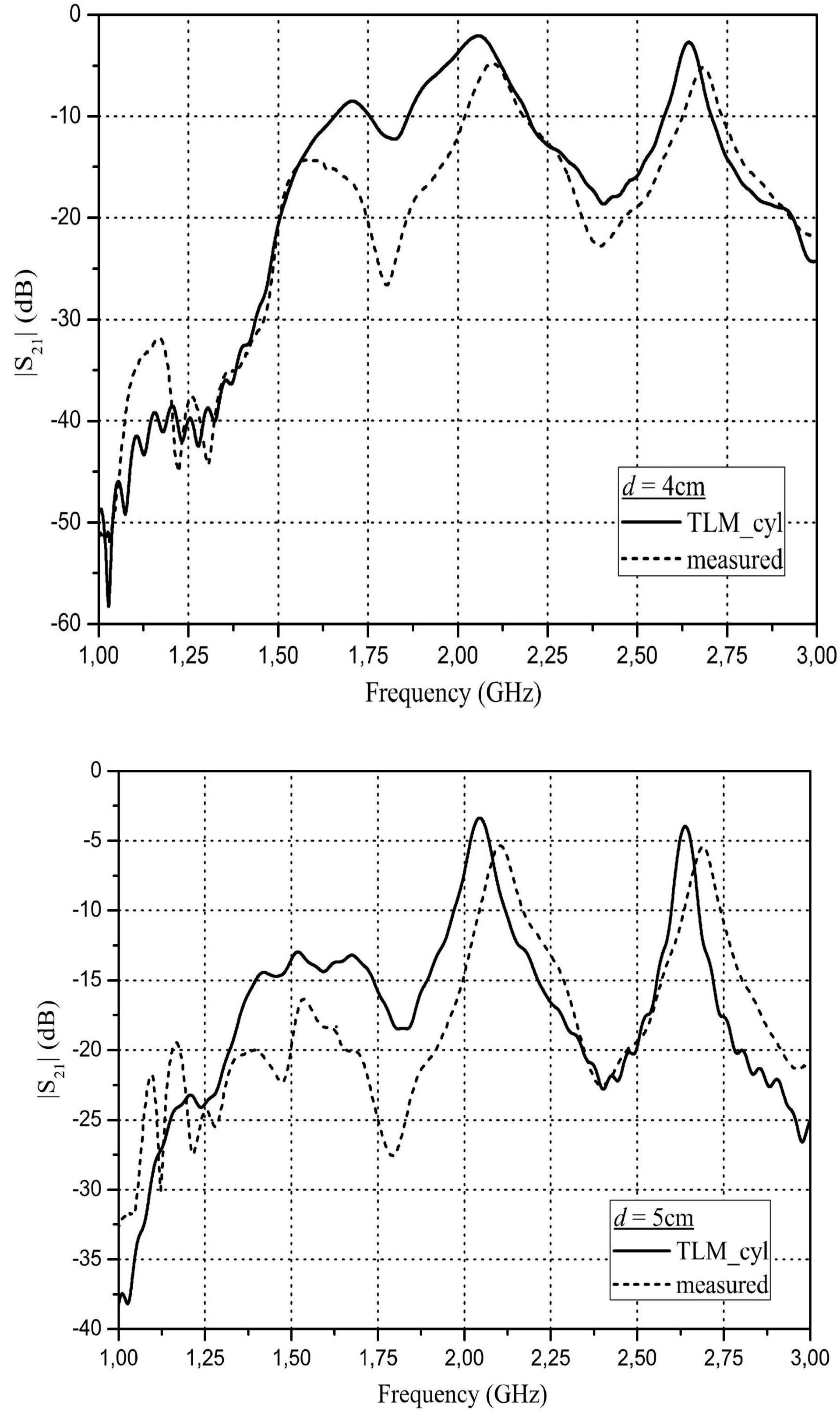
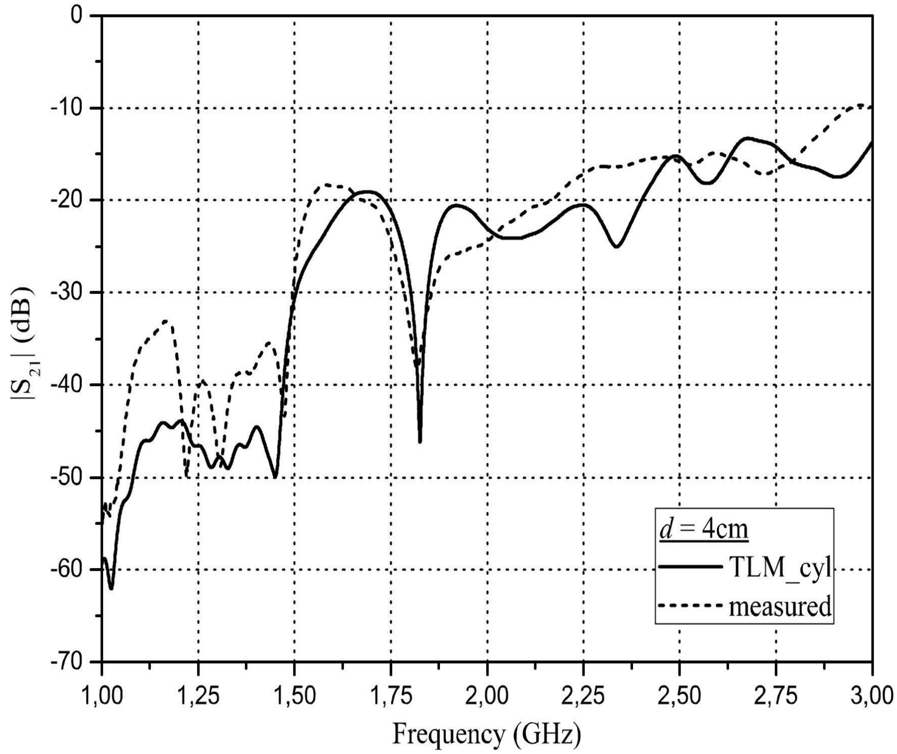


Figure 4. Transmission coefficient magnitude in the cylindrical cavity loaded with one water layer



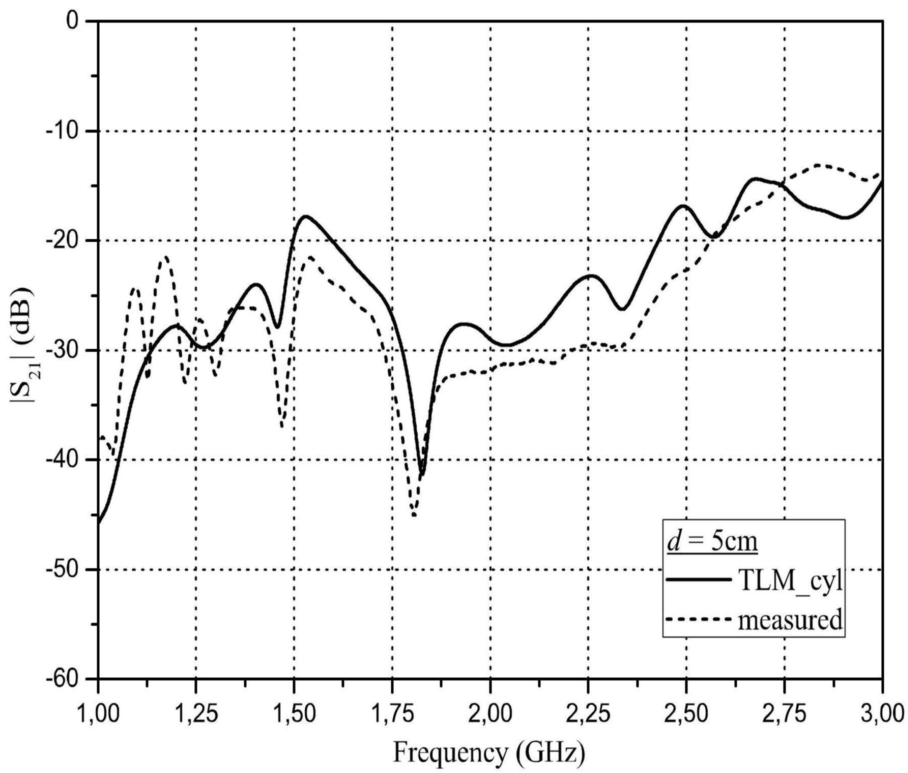


Figure 5. Transmission coefficient magnitude in the cylindrical cavity loaded with two water layers

into account (e_r = 77 - j6). For modelling purpose a cylindrical TLM grid ($\varphi \times r$) = (36×28) was used, whereas in z-direction dimensions of nodes are different, due to inhomogeneity of the medium inside the cavity. In order to achieve time synchronization of network, the TLM node in dielectric was set to be $\sqrt{\varepsilon_r}$ times less compared to the nodes dimension in the rest of the cavity filled with air.

Obtained numerical results, representing transmission coefficient in the frequency range of interest, have been experimentally verified in both cases of a loaded cavity and for variable lengths of probes. Figs. 4. and 5. present comparative results in terms of varying of probe length and load conditions. Apparently, a very good agreement between numerical and experimental results has been achieved, confirming that cylindrical mesh based TLM model can be used for analyses of probe-coupled cavity loaded with planparallel dielectric layers.

4. Conclusion

This paper presents an efficiency of the compact wire model implemented into the 3-D TLM cylindrical mesh for the purpose of the analysis of a probe-coupled loaded cylindrical microwave cavity. Due to cylindrical grid structure and empirical nature of the compact model, this implementation has to take into account a change of wire parameters with a variable cross-section of the TLM nodes through which a radially placed wire conductor passes. The model accuracy has been experimentally verified on an example of a probe-coupled cylindrical cavity containing one and two layers of water as a dielectric load, for different probe length values.

Considered configuration of a probe coupled cavity loaded with dielectric layers placed at different heights from the cavity bottom is of a great importance in a realization of microwave resonant applicators, widely used for thermal processing of materials.

Acknowledgement

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References

[1] Chan, T. V. C. T., and Reader, H. C. (2000). *Understanding microwave heating cavities*. Artech House.

[2] Balanis, C. (1989). *Advanced Engineering Electromagnetics*. John Wiley & Sons.

[3] Amnartpluk, S., Phongcharoenpanich, C., Kosulvit, S., and Krairiksh, M. (2003). A power divider using linear electric probes coupling inside conducting cylindrical cavity. *Int. Symp. on Circuits and Systems, 3*, 419-422.

[4] Milovanovic, B., Doncov, N., and Atanaskovic, A. (2001). Tunnel type microwave applicator analysis using the TLM method. *Proc. of the 4th International Workshop on Computational Electromagnetics in the Time Domain: TLM/FDTD and Related Techniques, CEM-TD 2001*, 77-84.

[5] Milovanovic, B., and Doncov, N. (2002). TLM modelling of the circular cylindrical cavity loaded by lossy dielectric sample of various geometric shapes. *Journal of Microwave Power and Electromagnetic Energy, 37*, 237-247.

[6] Jokovic, J., Milovanovic, B., and Randelovic, T. (2006). TLM Modelling of Microwave Applicator with an Excitation Through The Waveguide. *Microwave and Optical Computer Techonology Letters, 48*, 2320-2326.

[7] Ivkovic, S., Milovanovic, B., Marincic, A., and Doncov, N. (1997). Theoretical and experimental investigations of resonance frequencies in loaded cylindrical microwave cavity. *Proc. of the 3rd IEEE TELSIKS'97 Conference*, 306-309.

[8] Trenkic, V. (1995). *The development and characterization of advanced nodes for TLM method*. Ph.D. Thesis, University of

Nottingham.

[9] Trenkic, V., Wlodarczyk, A. J., and Scaramuzza, R. (1999). Modelling of coupling between transient electromagnetic field and complex wire structures. *International Journal of Numerical Modelling: Electronic Networks, Devices and Fields, 12*, 257-273.

[10] Jokovic, J., Milovanovic, B., and Doncov, N. (2006). TLM analysis of cylindrical metallic cavity excited with a real feed probe. *International Journal of RF and Microwave Computer Aided Engineering, 16*, 346-354.

[11] Jokovic, J., Milovanovic, B., and Doncov, N. (2008). Numerical Model of Transmission procedure in Cylindrical Metallic Cavity Compared with Measured Results. *International Journal of RF and Microwave Computer-Aided Engineering, 18*, 295-302.

[12] Milovanovic, B., Doncov, N., Jokovic, J., and Dimitrijevic, T. (2009). EM Field Monitoring in Circular Cavity Using Wire Compact Model Implemented in Cylindrical TLM Mesh. *Proc. of the TELSIKS 2009 Conference*, 339-342.

[13] Christopoulos, C. (1995). *The Transmission-Line Modelling (TLM) Method*. IEEE/OUP Press.