Numerical and Experimental Analysis of Electromagnetic Field in a Probe Coupled Cylindrical Metallic Cavity

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Abstract: - The procedure for analysis of electromagnetic field in a cylindrical metallic cavity, based on reflection and transmission characteristic, is presented in the paper. An analysis of procedure efficiency to resonant modes identification is conducted numerically and experimentally verified. As a numerical tool, TLM time-domain method, enhanced with the compact wire model to account for the presence of feed and monitoring probes, is used. Conditions, in terms of probe dimension, for achieving the best source matching and optimum coupling between ports, are considered. Results obtained using reflection and transmission procedures are also compared, in terms of modes identification and resonant frequency dependence of probe dimensions.

Key-Words: - Cavity, Wire, Probe, TLM Time-Domain Method, Reflection, Transmission

1 Introduction

Cylindrical metallic cavities represent a configuration very suitable for good modelling of practical microwave devices, such as applicators used in the processes of dielectric material heating and drying or filters and power dividers used for distribution of information in communications systems [1-3].

When practical realization is considered, one of the most important issues is the resonant modes distribution inside the metallic cavity, in order to achieve equally material drying or optimum transfer of energy.

There are many ways to couple energy into the cavity [1]. Generally, input and output ports of microwave cavity devices are realized by coaxial probe that ensures coupling with corresponding electromagnetic (EM) field component. Therefore, the reflection (S_{11}) and transmission (S_{21}) characteristics are common parameters in cavity exploration. The reflection parameter gives information about frequencies where energy enters the cavity and corresponding matching. However, in some applications S_{11} plots can not give all necessary information, because it does not reveal the nature of the excited mode. Therefore, the transmission parameter can be used to complete the picture of the mode distribution inside the cavity. In the cases which require monitoring of EM field inside the cavity or determining condition of optimum transfer of power in dividers based on coupled probes in cavity, two (or more) probes are needed for analyses purposes. Thus, the level of coupling between two ports can be determined through the transmission parameter.

Theoretically, the cavity is the space enclosed by the inner metal walls containing multiple resonant modes, whose frequencies are determined with cavity dimensions and EM properties of cavity loads [1]. However, in practice, the type and form of wire elements (probe and loop) used for cavity excitation and EM field monitoring have a significant influence to the number of modes resulting in a completely different case. For instance, placing the coaxial cable in the cavity will or will not generate the modes, depending on whether they have an electric field component in the direction of the source electric field. The resulting electric field will then be given as a sum of the modes excited in the cavity.

Another problem is accurate mode identification. Although the reflection and transmission characteristics plots give the number of modes in the cavity, they do not indicate exactly which modes are present. This situation is even worse when many modes are present. The probe presence also tends to shift the modes and sometimes split degenerate modes [1]. Furthermore, relative amplitudes of resonances are variable for different probe locations and dimensions. Generally, decision to identify resonant modes strongly depends on dimensions of monitoring probe and its position.

The knowledge of the mode tuning behaviour in a cavity under feeding/monitoring condition, that is physical and electrical probe parameters, forms an integral part of the studies in microwave techniques and it can considerable help in designing microwave cavity resonators [2,4]. As there is no analytical solution in the most cases of widely used cavities, computational EM techniques emerge as an invaluable tool in the cavity design [4-10]. Several numerical techniques are available for EM field studies; among them the finite difference time domain (FD-TD) [5] and transmission line matrix (TLM) [6], as known as full-wave methods, are most popular in the field. Also, the method of moments (MoM) is found to be a reliable technique for microwave applications with wire structures [2], while the finite element method (FEM) is found to be a reliable technique for microwave heating applications [7]. Also, neural networks can be used in order to investigate the mode tuning behaviour under loading condition [8]. Finally, measurement work has been done, in order to experimentally analyse of EM field in the cavity [1,2,9].

TLM (Transmission-Line Matrix) time-domain method is a general, electromagnetically based numerical method applied to variety of problems [6,9-13]. The influence of irregular dielectric shapes and its inhomogeneity to the resonant frequencies of the metallic cavities are investigated [9,10], where an impulse excitation was used to establish a desired mode distribution. However, this way of enhancing the wanted TE or TM mode is clearly different from the experimental procedure [9] where a wire probe, placed inside the cavity, is used as an excitation. Difference in the TLM and experimental model regarding the cavity excitation caused that the TLM results of resonant frequencies in the case of impulse excitation were shifted from the experimental ones. Therefore, improvement in the form of TLM wire node [12] was used to efficiently account for probe presence inside the cavity which allows accurate numerical investigation of the feed and monitoring probe influence to the resonant modes frequencies and level of EM field [13], detected from the S_{11} and S_{21} plots.

In this paper, the reflection and transmission procedure, based on the probes inserted into cylindrical metallic cavity, has been considered numerically and experimentally. Dimensions of the modelled cavity (Fig.1) are a = 7 cm and h = 14.24 cm, chosen to follow the experimental ones from [9]. Experimental cavity model for reflection and transmission characteristic measurement and the form of straight wire probes used in procedure are shown on the Fig.2.

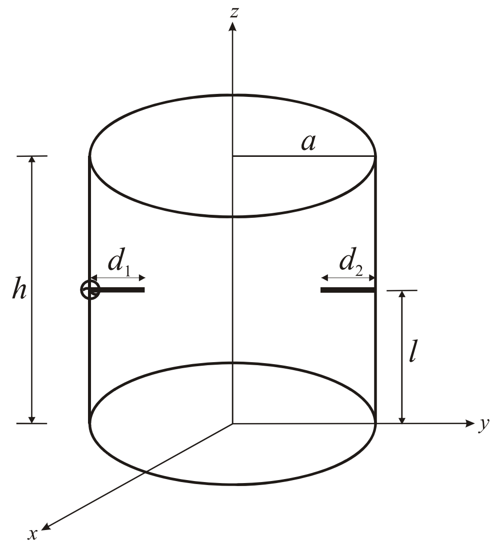


Fig.1 Model of cylindrical cavity with feed and receiving probes


a)


b)

Fig.2 a) Experimental cavity model and b) wire probe, used for reflection and transmission characteristic measurement

In the case of reflection procedure the same probe was used as feed and receiving probe. The feed probe is placed at the height l = 7.4 cm from the bottom on the cavity, slightly different from $h/2$, in the radial direction. In transmission method, this probe also was used as a real feed, while other was used to monitor established distribution of EM fields inside the cavity. In the case of transmission procedure receiving probe is placed at the same height and direction, opposite to feed probe. In this way, it is possible to excite and simultaneously detect modes having radial component of the electrical field in the cavity. Chosen position and dimensions of probes allow comparison of corresponding results of both procedures. In this cavity model influence of probes dimensions on resonant frequency and of TE and TM modes is taken into account.

The obtained numerical TLM results for modes in frequency range f = [1.5 - 3.5] GHz are validated against the experimental ones obtained by using the set up shown on the Fig.3.

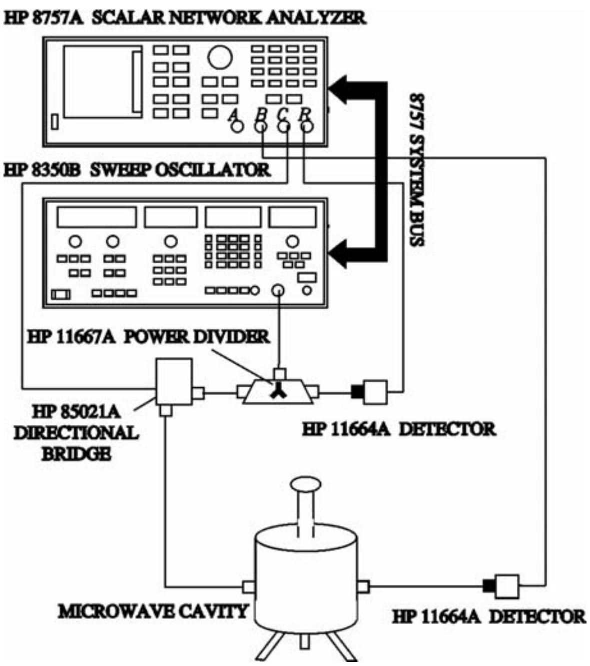


Fig.3 Experimental set up for resonant frequency measurement

2 TLM Model of Cavity with Probes

In the conventional TLM time-domain method, EM field strength in three dimensions, for a specified mode of oscillation in a cylindrical 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 [6]. EM properties of different cavity loads are modelled through network of interconnected nodes (Fig.4), a typical structure being the symmetrical condensed node – SCN (Fig.5). Additional stubs incorporated into TLM network to account for inhomogeneous materials and/or electric and magnetic losses. Generally, capacitance and inductance of TLM node can be expressed through link lines and stubs [6]:

$$C_{ik}\Delta i + C_{jk}\Delta j + C_o^k = \varepsilon_k \frac{\Delta i \Delta j}{\Delta k}, \qquad (1)$$

$$L_{ij}\Delta i + L_{ji}\Delta j + L_{ks}^k = \mu_k \frac{\Delta i \Delta j}{\Delta k}, \qquad (2)$$

where is $i, j, k \in \{x, y, z\}$ i $i \neq j, k$.

An efficient computational algorithm of scattering properties, based on enforcing continuity of the electric and magnetic fields and conservation of charge and magnetic flux [6] is implemented to speed up the simulation process.

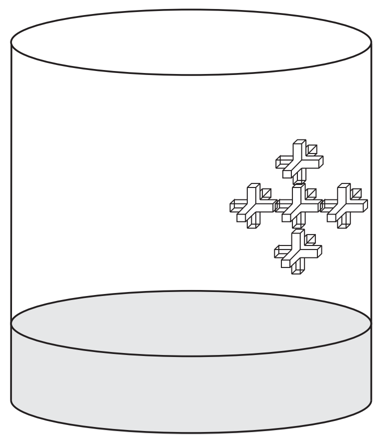


Fig.4. Cavity space modelled by the mesh of TLM nodes

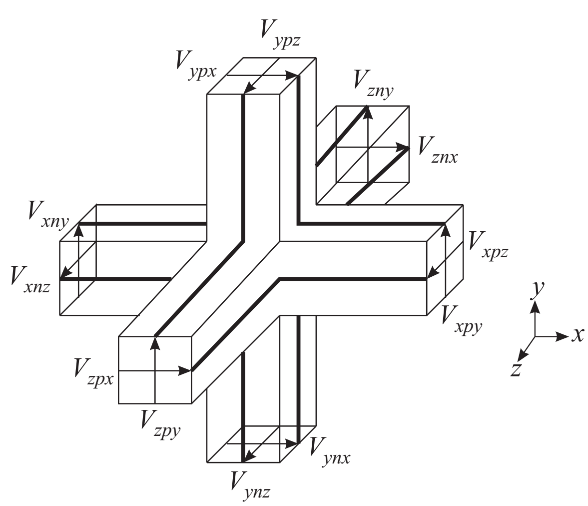


Fig.5. Symmetrical condensed node – SCN

Each node describes a portion of the medium shaped like a cuboid (Cartesian rectangular mesh) or a slice of cake (Non-Cartesian cylindrical mesh) depending on the applied coordinate system (Fig.6).

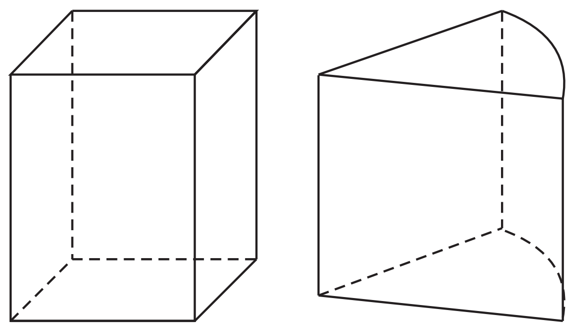


Fig.6. Portion of a medium in a rectangular or a cylindrical grid

Cavity walls in TLM time-domain method are described as boundaries. Generally, external boundaries of arbitrary reflection coefficient ρ_w are modelled in TLM by terminating the link lines at the edge of the problem space with an appropriate load [6]. If the characteristic impedance of a link line differs from the intrinsic impedance of a medium, the equivalent link line reflection coefficient, ρ_{ij}, will be different from ρ_w. The link line reflection coefficient, ρ_{ij}, can be found by terminating the link line, of characteristic impedance Z_{ij}, with the same resistance:

$$\rho_{ij} = \frac{R - Z_{ij}}{R + Z_{ij}} = \frac{(1+\rho_w) - \hat{Z}_{ij}(1-\rho_w)}{(1+\rho_w) + \hat{Z}_{ij}(1-\rho_w)} \tag{3}$$

where a normalized characteristic impedance is introduced as $\hat{Z}_{ij} = Z_{ij} / Z_{ij}^s$.

In the case of cavity model external boundary represents an electric wall, ($\rho_w = \rho_{ij}$). External boundaries modelling in TLM method, described by equation (3), will provide good results only if incident wave is perpendicular to the external boundary.

Wire probes, used for excitation and monitoring purposes inside the cavity, can be inherently described by additional link and stub lines interposed over the exiting network to account for increase of capacitance and inductance of the medium caused by their presence [12]. This wire network is usually placed in the centre of the TLM nodes (so called TLM wire node) in order to allow easy modelling of possible wire probe configurations (Fig.7). 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 [14], determined only by TLM mesh resolution.

The single column of TLM nodes, through which wire conductor passes, can be used to approximately form the fictitious cylinder which represents capacitance and inductance of wire per unit length. Its effective diameter, different for capacitance and inductance, can be expressed as a product of factors empirically obtained by using known characteristics of TLM network and the mean dimensions of the node cross-section in the direction of wire running [14].

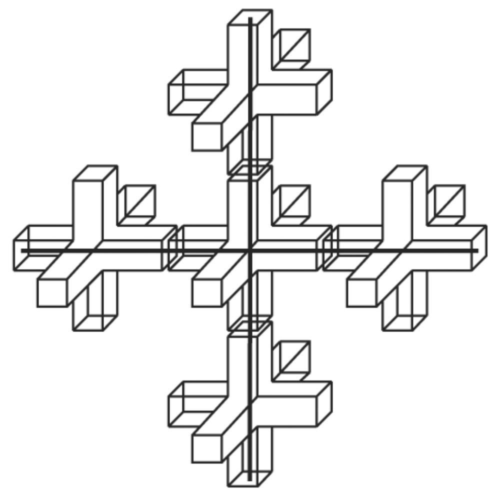


Fig.7 Wire network embedded within the TLM nodes

Requirement that the equivalent radius of fictitious cylinder is constant along nodes column can be easily met in a rectangular grid. However, in the cylindrical grid for wire conductor in the radial direction, mean cross-section dimensions of TLM nodes, through which wire passes, vary making difficult to preserve distributed capacitance and inductance of wire per unit length. Because of that, a rectangular grid has been chosen for modelling of cylindrical cavity analysed in this paper. At the same time, the numerical errors introduced by describing boundary surfaces of the modelling cavity in a step-wise fashion are reduced applying the TLM mesh with a higher resolution around cavity walls.

Following the experimental approach that using inner conductor of coaxial guide as a probe, numerical characterisation of EM field inside the cavity can be done by introducing wire ports at the interface between wire probes and cavity walls and calculating the scattering matrix. Model of wire port i incorporating in general voltage source $V_{source,i}$ and wire load $R_{port,i}$ is shown in Fig.8.

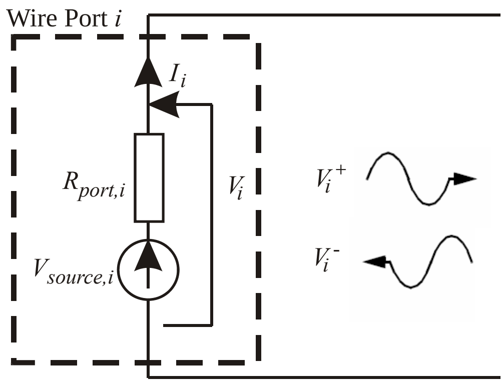


Fig.8. Equivalent circuit for TLM wire port i

As TLM wire node defined at wire port *i* gives wire current I_i and voltage V_i as output of TLM simulation, calculation of scattering matrix is straightforward. If wire port 1 is excited, S_{11} parameter, representing the reflection coefficient at wire port 1, can be calculated through wire port current I_1, or alternatively through wire port voltage V_1

$$S_{11} = \frac{V_1^-}{V_1^+} = 1 - \frac{2R_{port,1}I_1}{V_{source,1}} = \frac{2V_1}{V_{source,1}} - 1 \qquad (4)$$

In this case, S_{21} parameter, representing the transmission coefficient at wire port 2, for the case of equal port characteristic impedances ($Z_{c1}= Z_{c2}$) and taking into account that $V_{source,2}$ = 0, can be calculated through wire port current I_2 or alternatively through wire port voltage V_2

$$S_{21} = \frac{V_2^- / \sqrt{Z_{c2}}}{V_1^+ / \sqrt{Z_{c1}}} = -\frac{2R_{port,2}I_2}{V_{source,1}} = \frac{2V_2}{V_{source,1}} \qquad (5)$$

3 Results and Analyses

The results of modelling of the cylindrical cavity and analyses of EM field parameters are presented in this section. Numerical results of resonant frequencies and EM field level for modes in the frequency range f = [1.5 - 3.5] GHz are compared with analytical and experimental ones and analysed, in terms of influence of wire probes to EM field in the cavity.

3.1 Analytical verification of model

Having in mind the previously mentioned difficulties of wire modelling in the cylindrical grid, the numerical analyses of cylindrical cavity is done in rectangular grid. First, resonant frequencies of theoretical modes in cavity, obtained using rectangular grid model, are analysed in terms of accuracy and possibilities for modelling of cylindrical cavity.

Numerical TLM results, obtained in the case of impulse excitation and response (cavity without probes) are compared with corresponding analytical values [15] of resonant frequencies for TE and TM modes. In Table 1, the analytically calculated modes and numerical results, based on TLM rectangular network of 43×43×32 nodes ($\Delta x = \Delta y$ = 0.33 cm and Δz = 0.45 cm), are shown in the frequency range f = [1.5 - 3.5] GHz. Presented results of simulated modes, with error < 1%, completely confirm that applied rectangular grid model can be used for successfully modelling of cylindrical cavity.

Mode	*Resonant frequency [MHz]*		*Error [%]*
	analytical	*TLM method*	
TE_{111}	1639	1633	0.37
TM_{011}	1950	1951	0.05
TE_{211}	2334	2324	0.42
TM_{111}	2818	2812	0.21
TE_{212}	2993	3022	0.88
TM_{112}	3357	3388	0.92

Table 1. Comparison of analytically calculated modes and results of TLM modelling using rectangular network

3.2 Experimental verification and analyses

The results, which illustrate the possibilities and effectiveness of TLM method for modelling and analyses of the reflection and transmission procedure in the probe coupled cavity, are presented in this section.

Non uniform mesh defined in previous section, which allow incorporation of compact wire model, is used for cavity modelling. The influence of probes on EM field of TE and TM modes is taken into account. In order to modelling real coaxial cable characteristics, the feed probe is connected, through TLM wire port, with real voltage source: V_{source} = 1 V and R_{port1} = 50 Ω, and receiving probe is connected with impedance R_{port2} = 50 Ω.

3.2.1 Reflection procedure

First, using model of reflection procedure in cavity with one inserted probe, the resonant frequencies and EM field level in a cylindrical metallic cavity versus feed probe dimensions are analysed.

In order to investigate the influence of the length of wire conductor, to the resonant frequencies of the cavity, the radius of the feed probe is chosen to be r = 0.5 mm while the length d is changed in the range [1.0-6.0] cm. The obtained TLM numerical and experimental results of resonant frequencies for TE and TM modes in the frequency range f = [1.5-3.5] GHz, versus length of the real feed probe d, are shown in the Fig.9. A quarter-wavelength curve is presented in order to identify areas of capacitive and inductive character of probe input impedance.

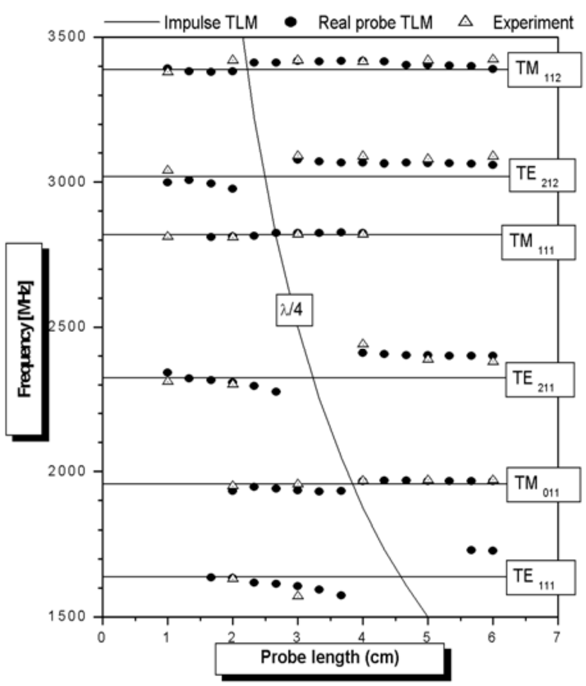
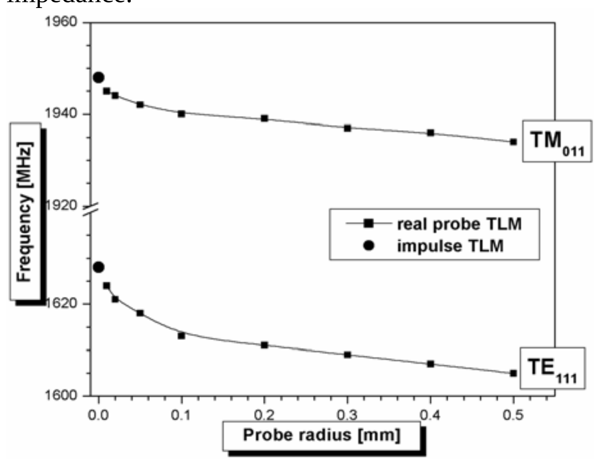


Fig.9. Resonant frequencies versus probe length for an empty cavity

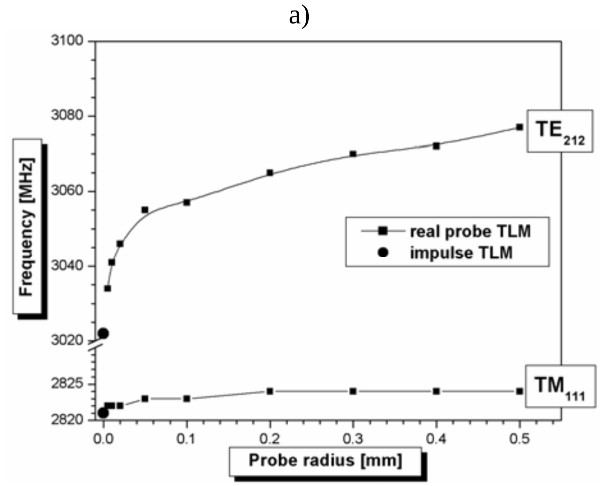
As it can be seen from Fig.9, in comparison with the conventional TLM approach with an impulse excitation (impulse TLM), the numerical results of resonant frequencies obtained with the wire node show a much better agreement with experimental ones.

In addition, the values of resonant frequencies for TM and TE modes considerable depend on the real feed probe length d, deviating around the conventional TLM results. In the case of TE modes having only radial component of electrical field, these deviations are much more noticeable than in the case of TM modes. In the area of capacitive character of probe input impedances (d < $\lambda/4$), both TLM and experimental results of resonant frequencies are below the conventional TLM results and with the increase of probe length, they tend to shift toward lower frequencies. In inductive area (d > $\lambda/4$) resonant frequencies have higher values than conventional results. However, due to increasing of probe length, these resonant frequencies are approaching the conventional results.

Further, in order to investigate the influence of the probe radius to the resonant frequencies of the cavity, TLM wire model is applied on the case where the length of real feed probe is constant (d = 3 cm) while the radius of feed probe r varies in the range [0.0-0.5] mm. Resonant frequencies curves versus radius of feed probe are presented in Fig.10 for modes excited in capacitive (TE_{111}, TM_{011},) and inductive (TM_{111}, TE_{212}) character of probe input impedance.



a)



b)

Fig.10. Resonant frequencies versus probe radius for modes in a) capacitive b) inductive character of probe input impedance

It should be noted that the frequency, corresponding to quarter-wavelength of probe used in this case, is f = 2.5 GHz (Fig.9). Therefore, in considered frequency range f = [1.5-3.5] GHz, the probe impedance has a capacitive character for frequencies in the range f = [1.5-2.5] GHz and an inductive character in the range f = [2.5-3.5] GHz. In the capacitive area (f < 2.5 GHz), TE_{111} and TM_{011} modes are excited. The values of resonant frequencies of these modes increase due to reducing of the probe radius and tend toward conventional TLM results (Fig.10.a). On the other side, in the area of inductive character of probe impedances (f > 2.5 GHz), due to reducing of the probe radius, the values of resonant frequencies of TM_{111} and TE_{212} (Fig.10.b), decrease and tend toward the conventional TLM results as well. Comparing the obtained results for all excited modes, it can be seen that TM_{111} mode has the least deviation of frequency versus probe radius: $f\,|_{r=0}$ = 2821 MHz, $f\,|_{r=0.5mm}$ = 2824 MHz. Also, it should be noted that, in this case, TE_{211} is not excited (Fig.9), because probe length d = 3 cm is approximately equal to corresponding quarter-wavelength for this mode frequency f_{res}= 2331 MHz (λ/4= 3.2 cm).

Also, from presented results it can be concluded that, in the case when probe presence shifts the mode frequency, we can determine which mode is exactly excited inside the cavity decreasing probe radius. This analysis can help in accurate determination of the modes, especially when many modes are present.

Besides resonant frequencies, the level of EM field detected from S_{11} characteristic is significantly different if probe length is varied. The Fig.9 already shows that for some probe lengths there is no possible detect all modes existing in the cavity. As an illustration of influence of probe length to level of EM field, in terms of conditions for achieving the minimum reflection for corresponding mode, the obtained numerical and experimental results of EM field strength, detected from S_{11}, versus probe length d, for the dominant TE_{111} mode, are shown in Fig.11. Other modes also have similar relative amplitudes dependence on probe length.

Both numerical and experimental results presented in Fig.11. confirm that reflection is at maximum for the values of small probe length as well as length corresponding to quarter-wavelength at TE_{111} mode frequency. This situation leads that for these lengths modes can not be detected from S_{11}. On the other hand, this dependence gives information which probe length should be chosen in order to achieve the minimum reflection for corresponding mode.

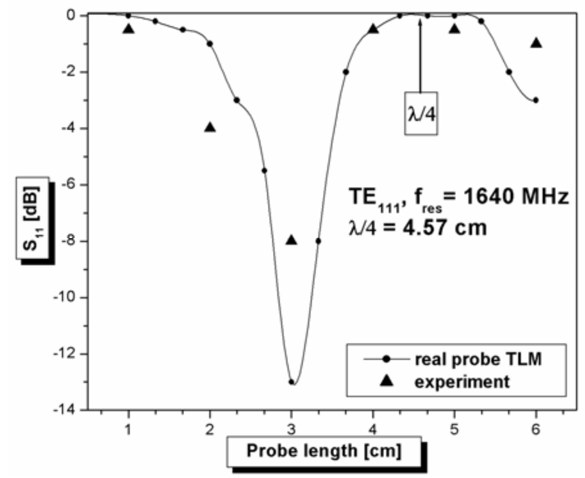


Fig.11. EM field strength versus probe length for TE_{111} mode

All previous analyses are done for an air-filled cavity but some conclusions are still valid for the loaded cavity. To the aim of illustrating agreement of numerical and experimental results, cavity loaded with lossy homogeneous dielectric sample, representing real microwave applicator, is analysed. The thickness of dielectric layer is 3 cm. As the microwave applicator is often used for drying of wet materials, which as a dominant element within itself have water, it is assumed that the permittivity of hypothetical lossy homogeneous dielectric sample is equal to that of water at a temperature 20°C. In the experimental system (Fig.3), the water sample is introduced in a convenient manner by using the system of connected test tubes.

As an illustration, S_{11} plot for the probe length d = 5 cm is shown in the Fig.12. The achieved agreement of obtained numerical results of frequencies and EM field level with the corresponding experimental ones indicates good TLM modelling of the real microwave applicator.

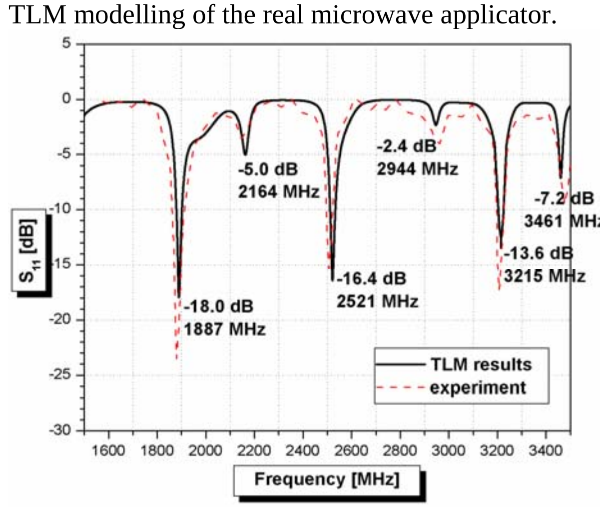
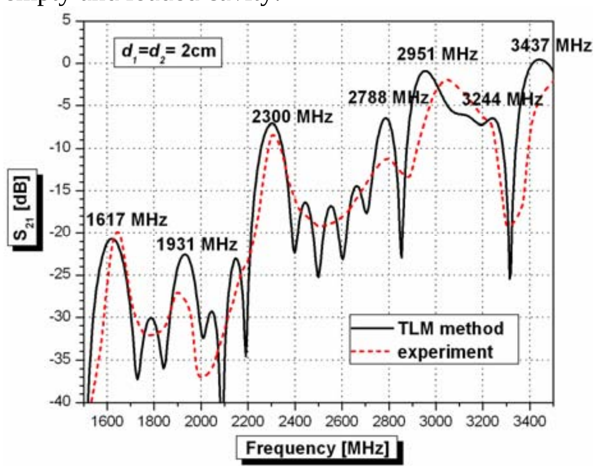


Fig.12. S_{11} plot for the loaded cavity

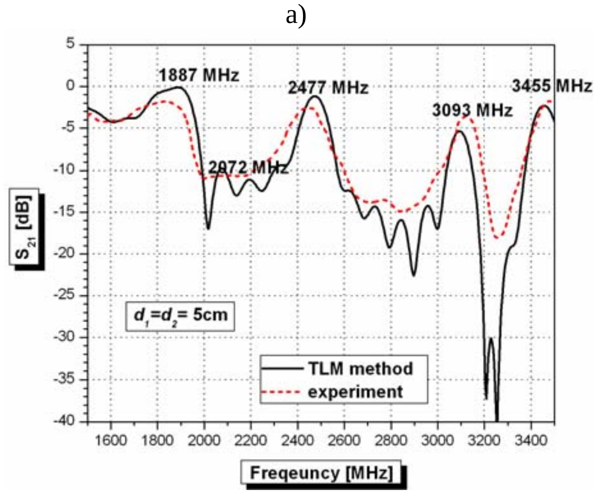
3.2.2 Transmission procedure

In order to experimental verification of numerical model of transmission procedure in cavity with two inserted probes, TLM result of S_{21} characteristic compared with the experimental one in the frequency range f = [1.5 – 3.5] GHz, is shown in Fig.13. The analysis is done for the case of empty cavity (air-filed), in the case of probe radius r = 0.5 mm and two characteristic length of probes: d = 2 cm (capacitive probe) and d = 5 cm (inductive probe). It can be noted that the TLM results obtained with the wire node follow the experimental values of resonant frequencies and corresponding values of detected EM field level, in the both cases.

Besides, results representing transmission characteristics in the case of cavity loaded with lossy homogeneous dielectric sample (water at a temperature 20°C, with thickness of 3 cm) are shown in Fig.14. Presented results confirm possibilities of TLM method as a tool for modelling and analyses of transmission procedure in both empty and loaded cavity.



a)



b)

Fig.13. S_{21} plot for empty cavity in the case of a) capacitive, and b) inductive probe

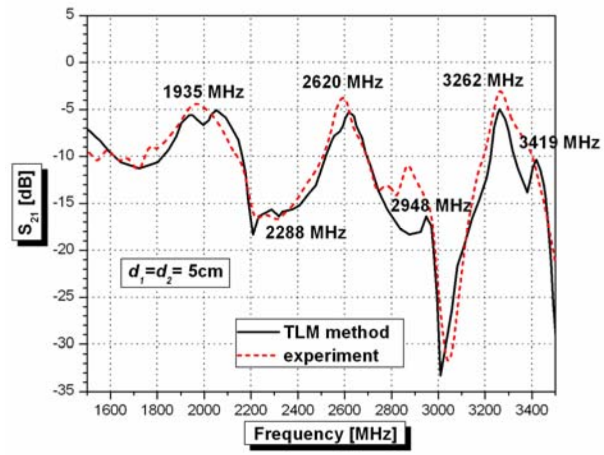


Fig.14. S_{21} plot for loaded cavity

In Fig.15 comparison of transmission characteristics for different probes length are shown, in the case of air-field cavity. As in the case of reflection procedure, presented results also show significant resonant frequency and level of EM field dependence of probes length. From Fig.15, one can conclude that deviation of resonant frequencies from theoretical values of all modes is different - positive or negative, depending on probe dimension related to input impedance character.

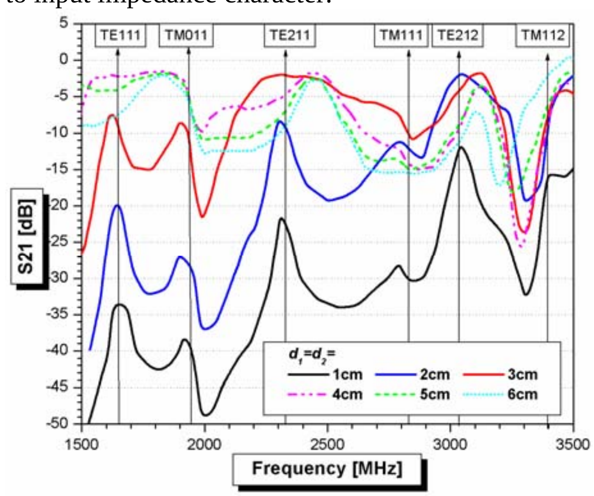


Fig.15. Comparison of S_{21} plots versus probes length

As an illustration, the obtained numerical results of resonant frequencies versus probes length d, for the mode TE_{211}, are shown in Fig.16. As it can be seen, the values of resonant frequency considerable depend on the probe length d, deviating around the conventional impulse TLM results, depending on probe dimensions and reactive character of probe input impedances. However, in the case of transmission procedure (two probes), these deviations are much more noticeable than in the case of reflection method (one probe).

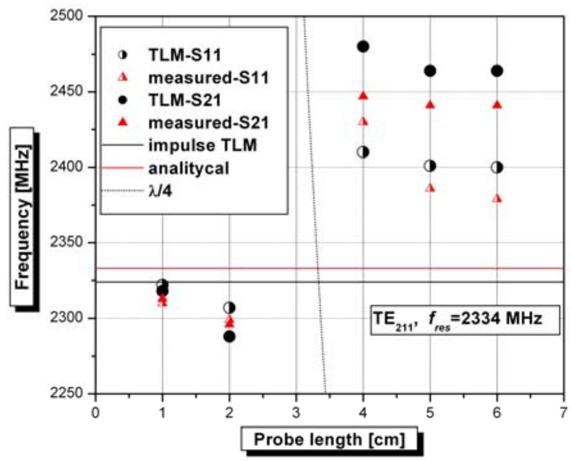


Fig.16. Deviation of TE_{211} mode frequency versus probe length

Also, from Fig 15, it is noted that level of EM field, detected from S_{21} depends on probe length. In previous section influence of probe length to level of EM field, detected from S_{11} are investigated and presented results in Fig.11 show that reflection is maximum, that is mode is not detected, for the values of probe length corresponding to quarter-wavelength at mode frequency, as well as small probe length (d = 1cm). In the case of transmission procedure, detection of modes is possible even in the case of small probe lengths. As an illustration, reflection and transmission characteristics (S_{11} and S_{21}) plots for the probe length d = 1 cm is shown in the Fig.17. It can be noted that in these cases S_{21} is more convenient for precise mode identification. However, there are probe length when reflection procedure gives better results, therefore for complete analyses and modes detection it is needed to use both reflection and transmission procedure.

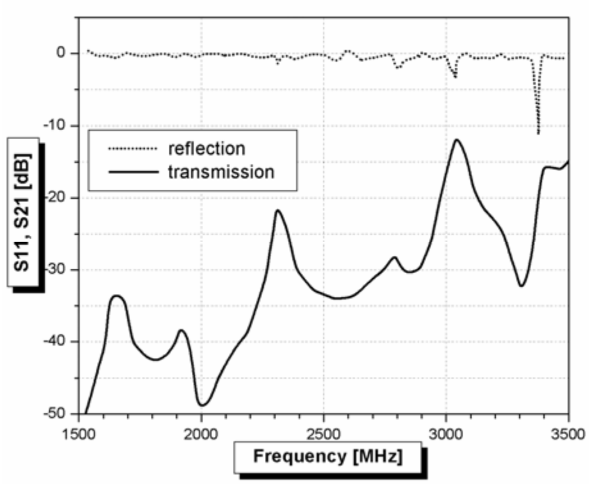


Fig.17. Comparison of S_{11} and S_{21} characteristic for probe length d = 1 cm.

4 Conclusion

In this paper, the TLM numerical technique has been applied to the problem of analysis of electromagnetic field in the cylindrical cavity using reflection and transmission procedure. The influence of the feed and receiving probe dimensions to the resonant frequencies and level of EM field, as important information in the microwave cavity design, is numerically investigated and experimentally verified.

The obtained results, where a probe inside the cavity is used as a feed, show that values of resonant frequencies considerable depend on wire dimensions related with a character of probe impedances. According to results obtained by transmission procedure, deviations of frequency versus probes length are greater in the case of two probes inserted in the cavity. Monitoring probes are additionally shift frequency of modes from theoretical values.

Significance of this approach is that TLM technique gives information which dimensions and position of feed probe should be chosen to the aim of achieving the best source matching, as well as, receiving probe for optimum coupling between ports in operating frequency range, in the real case of microwave applications based on cavity resonators.

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