Modeling of Circular Cylindrical Metallic Cavity Loaded by a Lossy Dielectric Sample of Various Geometries Using 3-D TLM Method

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Abstract

Analysis of cylindrical metallic cavity with circular cross-section, loaded by a lossy dielectric sample of various geometries is performed using the Transmission-Line Modeling (TLM) method. For modeling purpose, a hybrid symmetrical condensed node (HSCN) in cylindrical coordinates, implemented in appropriate software, is applied. Influence of the load effect on the resonant frequencies of the cavity is investigated for several characteristic geometries of the dielectric sample. Applied modeling approach is also experimentally verified.

Introduction

Utilisation of microwaves in industry has led to the development of a number of microwave applicators. Cylindrical metallic cavity with circular cross section is sometimes used in the processes of dielectric material heating and drying. Some experimental results [1,2] and theoretical investigations based on the transverse resonance method [1,2,3] of the circular cylindrical cavity loaded by planparallel lossy dielectric layers (Fig.1*a*) have been accomplished. However, in some practical cases, dielectric sample can have more complex shape and modeling of such structures is more difficult using this method. The Transmission-Line Modeling (TLM) method [4,5,6] provides numerical procedure that is highly suitable for modeling of structures of irregular geometry, but until now, only an effect of load inhomogeneity in radial direction has been analyzed [7] using this approach.

The TLM method is a time domain numerical method used for solving a great variety of electromagnetic-wave propagation problems. A permanent problem in electromagnetic modeling, in general, is how to achieve a good description for arbitrary geometry. Irregular boundaries can be handled in TLM by using Cartesian mesh or orthogonal curvilinear mesh approaches [8]. In the Cartesian mesh approach, curved walls are described in a step-wise fashion, which induces spurious modes. This approach is not acceptable in a number of problems. Cylindrical geometry modeling enables describing boundary conditions more accurately and saves computer storage by exploiting symmetry problem.

In this paper, several characteristic geometries of dielectric load are modeled using 3-D TLM algorithm for orthogonal curvilinear mesh. Three cases of load form are considered: lossy dielectric sample of thickness t placed in the bottom (Fig.1*a*), lossy dielectric sample inhomogeneous in θ direction (Fig.1*b*) and lossy dielectric sample sloped by angle α in regard to the cavity base (Fig.1*c*) (inhomogeneous in r and θ direction). An electromagnetic field response of the cavity in time and frequency domain is obtained using non-uniform cylindrical mesh, pulse excitation to establish desired field distribution in the cavity and by implementing hybrid symmetrical condensed node (HSCN) in cylindrical coordinates in developed software [9]. From this response, resonant frequencies of the available experimental cavity (Fig.2) for all cases of the load form are calculated and compared with experimental results.

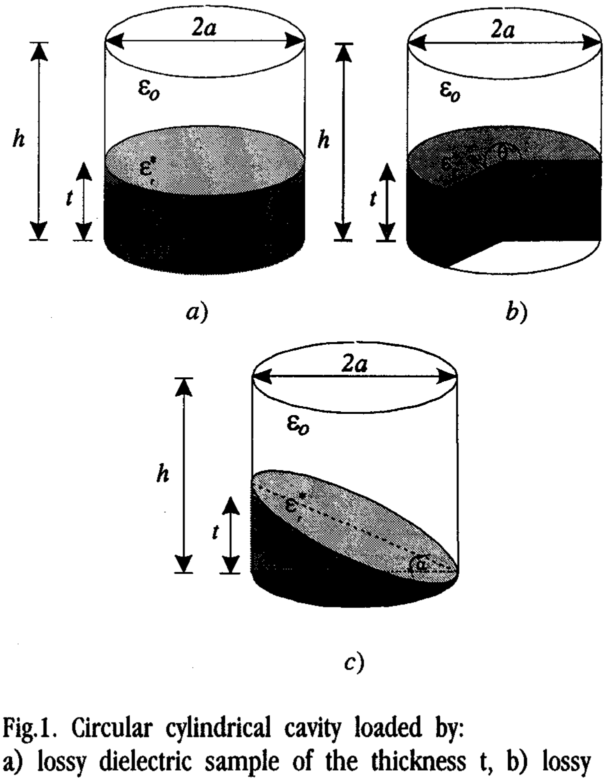


Fig.1. Circular cylindrical cavity loaded by:
a) lossy dielectric sample of the thickness t, b) lossy dielectric sample inhomogeneous in θ direction, c) lossy dielectric sample sloped by angle α in regard to the cavity base.

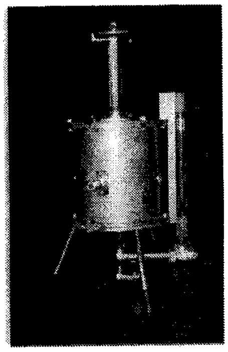


Fig.2 Experimental circular cylindrical cavity.

Theoretical Analysis

Many electromagnetic problems require simulation in three dimensions and for this purpose the appropriate TLM models are developed [4]. Independently of applied model, boundary surfaces of the modeling medium must lie on coordinate surfaces of the coordinate system defined by the mesh in order to impose necessary field boundary conditions. Clearly, in order to represent essentially cylindrical structures, such as cylindrical cavity which is of interest here, a cylindrical mesh of transmission lines, rather than a Cartesian mesh, is used.

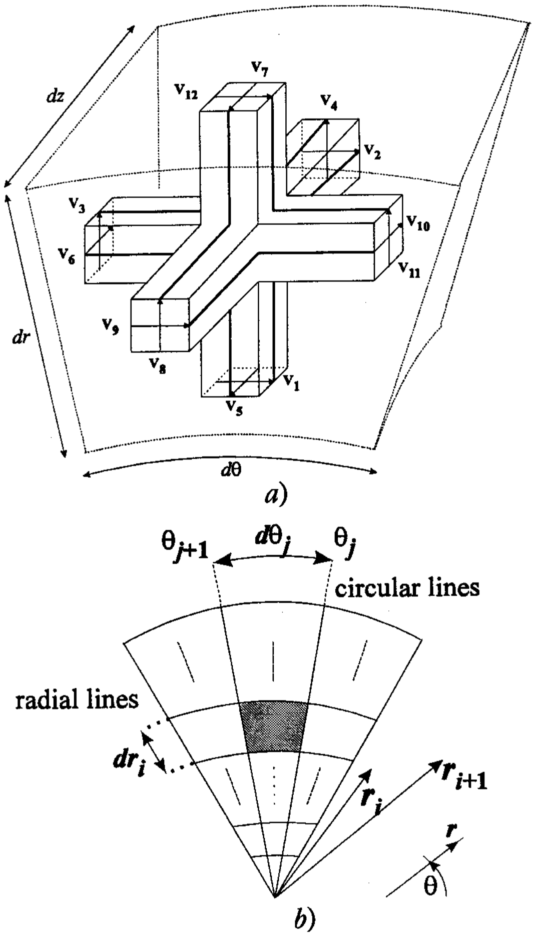


Fig.3 a) Symmetrical condensed node (SCN) in cylindrical coordinates, b) medium modeling in rθ plane.

Symmetrical condensed node (SCN) is often used for 3-D simulation of block of medium. Its basic form for orthogonal polar mesh is shown in Fig.3*a*. To model inhomogeneous media, stubs are added to the basic structure in order to increase capacitance (ε) and/or inductance (μ) (stab-loaded node). This node may be modified to eliminate either the inductive or capacitive stubs. In the resulting hybrid SCN, there are three different link-line impedance values and three stubs. Simulation proceeds exactly as for a HSCN in a Cartesian grid. This modification involves the calculation of stub parameters in accordance with new geometry, i.e. cylindrical coordinates.

Modeling Problem

In the orthogonal polar mesh, medium is presented in $r\theta$ coordinate plane by cells or elements of different size (dr_i ,$d\theta_j$) (Fig.3*b*) where *i* refers to radial lines and *j* refers to circular lines; $dr_i = r_{i+1} - r_i$ and $d\theta_j = \theta_{j+1} - \theta_j$. Lossy dielectric sample inhomogeneous in θ direction (Fig.1*b*) is divided into *n* dielectric layers of small thickness (Fig.4). Used approach is very suitable for modeling of this load form because the plane interface *a0a'*, formed by regions (1) and (2) with different relative permittivities ε_r^* and ε_0, respectively, coincides with radial lines. Resolution of the TLM cylindrical mesh in θ direction for region (1) is bigger than resolution for region (2) (ratio $d\theta_1/d\theta_2 < 1$ and it depends on the ratio of relative permittivity in regions (1) and (2)).

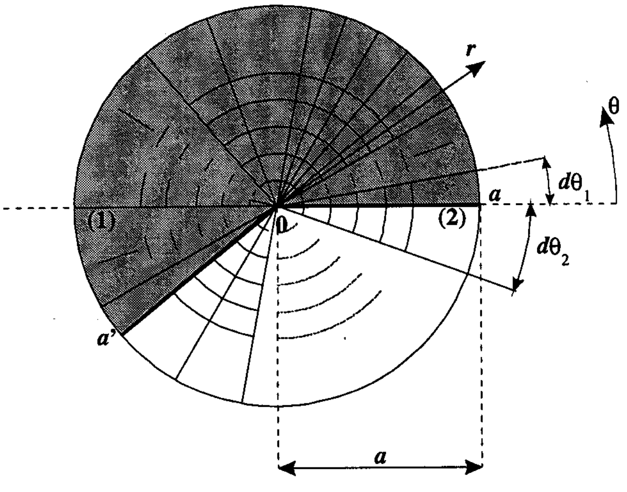


Fig.4 K-th layer (k=1,...,n) of the dielectric sample inhomogeneous in θ direction in rθ plane.

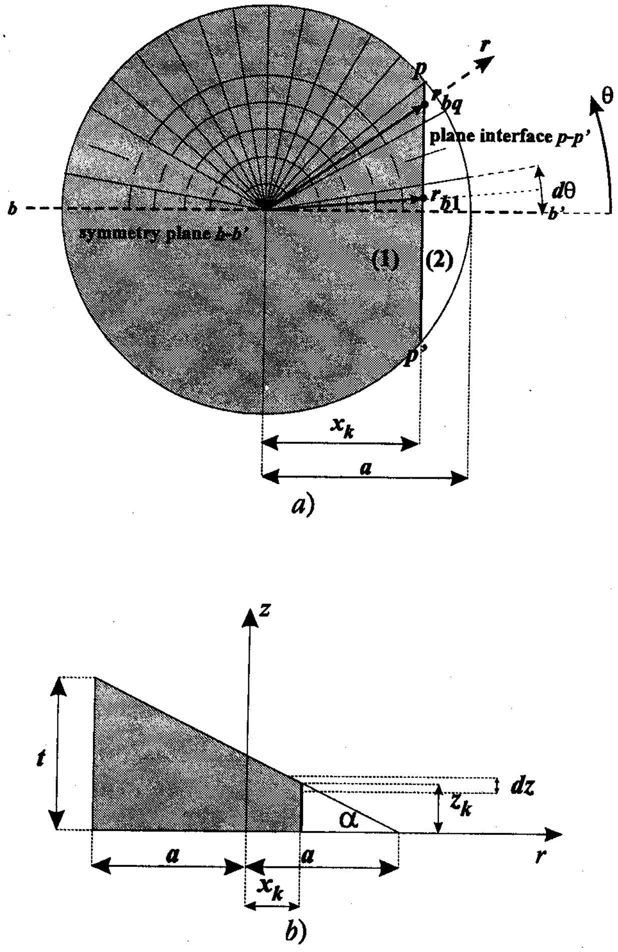
Sloped lossy dielectric sample (inhomogeneous in *r* and θ direction) (Fig.1*c*) is modeled in form of *m* dielectric layers (Fig.5*a*) of small thickness *dz* (Fig.5*b*). The plane interface *p-p'*, formed by two regions ((1) and (2)) with different relative permittivities ε_r^* and ε_0, respectively, is defined by vector of points whose location in radial direction r_{b_s} is determined by resolution of the mesh in θ direction and it can be written for k-th dielectric layer as:

$$r_{bs} = \frac{x_k}{\cos((2s-1)\,d\theta/2)} \quad \text{for} \quad s=1,..q. \quad (1)$$

Distance between plane interface for k-th layer and cavity centre x_k can be found from Fig. 5*b*:

$$\frac{z_k}{a-x_k} = tg\alpha \quad (2)$$

where: α – slope angle of the dielectric sample in regard to the base of the cavity, *a* – radius of the cavity and z_k – distance between centre of k-th dielectric layer and base of the cavity.
In the modeling approach we considered that for $r_{i,j} \le r_{b_j}$ the cell belongs to region (1) and for $r_{i,j} > r_{b_j}$ the cell belongs to region (2).



a)

b)

Fig.5 K-th layer (k=1,...,m) of the dielectric sample sloped in regard to the cavity base in:
a) rθ plane, b) rz plane.

Numerical Results

Experimental cylindrical cavity with dimensions $2a=14$ cm and $b=14.24$ cm (Fig.2) is modeled by 3-D TLM method. First, the load in the form of dielectric sample of the constant thickness *t*, placed on the bottom of the cavity (Fig.1*a*), is analyzed. Water, whose relative dielectric constant is calculated from Debby's formula [10] at the temperature of 20°, is used as a lossy dielectric. Cylindrical TLM mesh is excited with pulse excitation H_θ to enhance the TM_{011} mode [11]. The circle in the centre of the mesh is considered as an open-circuit boundary. The same mode is established in the experimental cavity (Fig.2) by using a coupling loop at the end of the coaxial line. Numerical results of the resonant frequencies calculated for several values of filling factor (t/h) as well as measured results are shown in Fig.6. It can be noted that numerical results are in good agreement with measured results.

The influence of the load inhomogeneity in θ direction (Fig.1*b*) on resonant frequencies in experimental cavity is investigated using 3-D TLM and the results are presented in Table 1 for some characteristic values of parameter θ (Fig.1*b*) and t/h=0.1.

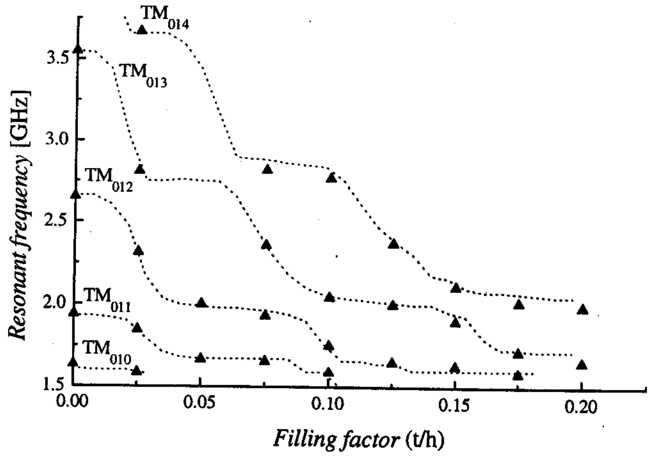


Fig.6 Resonant frequencies for TM_{011} mode versus filling factor (t/h):
a) calculated using 3-D TLM method (▲) and
b) measured results (dotted line)

Case θ=0° for TM_{010} mode (empty cavity) and cases θ=0° and θ=360° for TM_{011} mode are previously calculated (see Fig.6).

θ(°)	*f* (GHz), (TM_{010})	*f* (GHz), (TM_{011})
0	1.6300	1.9396
45	0.7270	1.8167
90	0.6719	1.7614
135	0.6485	1.6584
180	0.6345	1.5954
360	0.5991	1.5892

Table 1. Resonant frequencies for t/h=0.1 and several characteristic values of parameter θ.

From the results presented in Table 1. it can be seen that resonant frequency decreases by increasing the parameter θ.

Further, the more complex geometry of the water sample (inhomogeneous in *r* and θ direction) (Fig.1*c*) is analyzed. Dimensions of TLM mesh which is used for cavity modeling are 20×32×*Nz*. Number of nodes in *z* direction–*Nz* has been increased for bigger values of α keeping accuracy of modeling. Symmetry is used around the plane running through the axis of the cavity (symmetry plane *bb'*). Resonant frequencies calculated using 3-D TLM method as well as measured results are given in Table 2 for several values of α. It can be seen that there is a good agreement between numerical and experimental results and that the resonant frequency mostly increases with increase of the slope angle.

α=5°		α=15°		α=25°		α=35°		α=45°	
f(GHz) (TLM)	f(GHz) (Exp.)	f(GHz) (TLM)	f(GHz) (Exp.)	f(GHz) (TLM)	f(GHz) (Exp.)	f(GHz) (TLM)	f(GHz) (Exp.)	f(GHz) (TLM)	f(GHz) (Exp.)
1.581	1.60	1.589	1.62	1.626	1.62	1.604	1.61	1.613	1.63
1.702	1.72	1.772	1.79	1.834	1.87	2.043	1.98	2.046	2.08
2.358	2.37	2.417	2.42	2.457	2.47	2.526	2.59	2.849	2.86
2.776	3.05	2.805	3.07	2.859	3.09	2.888	3.12	3.453	3.53

Table 2. Numerical and experimental results of the resonant frequencies for several values of α

Conclusion

Analysis of load effect on the resonant frequencies in cylindrical metallic cavity with circular cross-section, using 3-D TLM method is carried out in this paper. The case when load is in the form of lossy dielectric sample located in the bottom of the cavity is considered as well as the case when lossy dielectric sample has more complex geometry. Numerical results of resonant frequencies are experimentally verified on the example of experimental circular cylindrical cavity in the case when water is used as a dielectric sample. Good agreement between numerical and experimental results shows that applied TLM modeling approach is highly suitable for modeling the structures which are examined in this paper.

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