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Verified simulation of waveguide inhomogeneities in Keysight EMPro 2017 software

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Abstract. In this paper numerical simulation of inhomogeneities in rectangular and circular waveguides at microwave, using the finite element method in Keysight EMPro 2017 CAD, with experimental data verification are considered. A sphere is used as a typical heterogeneity. Four samples of materials are considered: copper, paraffin, acrylic resin and texolite. A description is given for the modeling the electrophysical parameters of these materials in a computer-aided design system. A comparison of numerical and experimental data for a rectangular waveguide is made. The selected materials are of primary concern for the study and demonstrate various electrophysical parameters.

Keywords. Waveguide, sphere, finite element method, modeling, ECAD, reflection coefficient

Экспериментально верифицированное моделирование неоднородностей в волноводах в программе Keysight EMPro 2017

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Аннотация. В данной работе рассматривается численное моделирование неоднородностей в прямоугольном и круглом волноводах на СВЧ, используя метод конечных элементов в САПР Keysight EMPro 2017, верифицируемое экспериментальными данными. В качестве типовой неоднородности используется сфера. Рассматриваются четыре образца материалов: медь, парафин, оргстекло и текстолит. Приводится описание способов описания электрофизических параметров этих материалов в системе автоматизированного проектирования. Приводится сравнение численных и экспериментальных данных для прямоугольного волновода. Выбранные материалы демонстрируют различные электрофизические параметры и представляют особый интерес для изучения.

Ключевые слова. Волновод, сфера, метод конечных элементов, моделирования, САПР, коэффициент отражения

1. Introduction

The restoration of the electrophysical parameters of inhomogeneities distinguishable in the transmission line with cavities, such as a waveguide is the main requirement of the work. The basis of this study, including the use of numerical methods of electrodynamics is described [1]. The generalized methodology must be verified, due to the lack of uniqueness of the solution when using numerical methods, as well as to conduct modeling with controlled accuracy. ECAD EMPro with a FEM engine to solve the problem is used in the study. As a typical inhomogeneity, for which a full-scale verification was performed, a sphere with different electrophysical parameters is used. Both rectangular and circular waveguides operating on microwave are considered. An effective mathematical apparatus for analyzing diffractions on inhomogeneities in a circular waveguide is presented [2].

Numerical simulation of inhomogeneities in waveguides, using the finite element method, with experimental verification is considered in this paper. Data on the numerical analysis of such systems are presented [3]. Information on the numerical simulation of materials in EMPro is presented in the book [4].

Experimental investigations have been conducted initially. Its detailed descriptions are presented in the works: [5–7]. The measuring system is presented in the work [8], however, the measurement method is fundamentally different and the reconstruction of Mie equations for closed space is used.

2. Simulation

Two types of waveguide operating in single mode in the microwave range: rectangular 23 x 10 mm and circular with the radius 15 mm are analyzed. The simulation is carried out in accordance with the stable mode of the experiment at frequencies 8–12 GHz. As a reference inhomogeneity, a sphere with a radius of 2.25 mm is used, which corresponds to the Rayleigh range.

EMPro with FEM solver is optimized in manual mode to achieve the required accuracy, without taking into account the possibilities of time-precision optimization, since at this stage the study of the possibility of reducing the simulation time without loss of accuracy is not a priority. Mesh optimization of dielectric objects is performed using the previously obtained algorithm [9].

Table 1 demonstrates sample materials that are studied in this work. The table presents the experimental parameters of materials (except for copper, the conductivity (σ) of which is taken from reference sources) based on the results of work [10]. The table uses the classic notation, where $\mathrm{Im}(\varepsilon_r)_{rel}$ – the value of the imaginary part of the permittivity at the relaxation frequency f_{rel} of the dielectric.

Table 1. Parameters of the studied materials

N	*Material*	*Parameters for 8–12 GHz*
1	Copper	$\sigma = 5.8 \cdot 10^7$, S/m
2	Acrylic resin	$Re(\varepsilon_r) = 2.53–2.57$; $Im(\varepsilon_r) = 0$; $Re(\mu_r) = 1$; $Im(\mu_r) = 0$.
3	Paraffin	$Re(\varepsilon_r) = 2.14–2.30$; $Im(\varepsilon_r) = 0.24–0.47$; $Re(\mu_r) = 1–0.90$; $Im(\mu_r) = 0–0.15$.
4	Texolite	Demonstration of a causal nature [11]. $Re(\varepsilon_r) = 3.57–2.12$; $Im(\varepsilon_r) = 1.39–0.30$; $Im(\varepsilon_r)_{rel} = 2.00$; $Re(\mu_r) = 0.90$; $Im(\mu_r) = 0.20–0.23$; $f_{rel} = 9.77$ GHz.

2.1. Simulation parameters

We are drawing to exact modeling, in this regard the waveguides material corresponds to that used in the experiment, namely copper. The air box is modeled in the waveguide cavity. Waveguide ports are configured for a single mode regime for the fundamental waves as a rectangular and circular waveguide.

An adaptive type of frequency plan is used. Maximum number of analyzed points is 200. Solution stopping criterion $\Delta Err = 0.002$ – relative error. Target initial mesh size equal to ($\lambda_{max}/10$), where λ_{max} – wavelength at maximum frequency. Solver uses the 2nd order discretization for direct matrix solution. An adaptive finite element mesh is superimposed on the structure. Heterogeneity has a local mesh size optimized by the principle of maximum electrical significance [9].

2.2. Description of material parameters

To achieve the goal of high-precision modeling, when describing the parameters of materials, functional algorithms are used. Consequently, in the case of the metal sphere (*N* 1 in table 1), when setting the parameters, the surface conductivity correction is selected. In this case, volumetric finite element mesh is generated. This procedure significantly increases the calculation time, however, it was obtained that the influence of the skin layer affects the parameter more significantly than the total computational and measurement errors. Even a visual assessment of the results shows the difference. Due to the fact that in this paper the problem of minimizing or searching for modeling errors is not solved, no accurate analysis and assessment of this effect is implemented.

When modeling acrylic resin (N 2 in table 1), based on the values of table 1, the magnetic permeability of a material is as free space. This assumption is justified and does not cause doubts, by virtue of conducting an experiment on the microwave.

The assignment of electrophysical parameters of paraffin (N 3 in table 1), is similar to the case described above, except for the fact that the specification of magnetic permeability is mandatory.

The most difficult is the modeling of complex materials, the frequency curl of the parameters of which demonstrates a causality character, due to various kinds of impurities, which leads to the emergence of new types of material polarizability. In this paper, such materials are texolite (composite epoxy material). EMPro has all the necessary functionality to describe such materials. We use the classic description of the material by Djordjevic [11]. It has much in common with the Debye characteristic (in the open literature, sometimes these concepts are identical). In general, it is not difficult to move from the Debay description to Djordjevic, since the second one is broader. Using the terms of the Debye relaxation we have:

$$\varepsilon_r(f) = \varepsilon_\infty + \frac{\Delta\varepsilon}{1+\left(f/f_{rel}\right)^2}, \tag{1}$$

where ε_∞ – the dielectric constant of the material at frequency goes to infinity and $\Delta\varepsilon$ – difference in value for extreme frequencies of analysis. Djordjevic description is as follows:

$$\varepsilon_r(f) = \varepsilon_\infty + a \cdot \ln\frac{f_H + j\cdot f}{f_L + j\cdot f}. \tag{2}$$

The indisputable advantage of the expression (2) is the complex nature of the magnitude, which corresponds to the dielectric with losses, as in our case (N 4 in table 1). The coefficient of magnitude a is not set manually, but is calculated automatically by EMPro. However, it is not difficult by varying this value to achieve a complete (or almost complete) correspondence between (1) and (2). In our case a = 3.2. Values f_H and f_L – extreme frequencies of analysis. Obviously, f_H = 12 GHz and f_L = 8 GHz. In accordance to material specification the evaluation frequency f_E has to be specified. This frequency is the frequency of the correspondence of the electrophysical parameters to the classical complex form. Empirical method gives compliance between f_{rel} and f_E. In the calculation of the model, the equality $f_{rel} = f_E$ is used. Fig. 1 shows a comparison of two frequency characteristics for material N 4. This shows the complete validity of using the algorithm for describing material parameters through the EMPro environment.

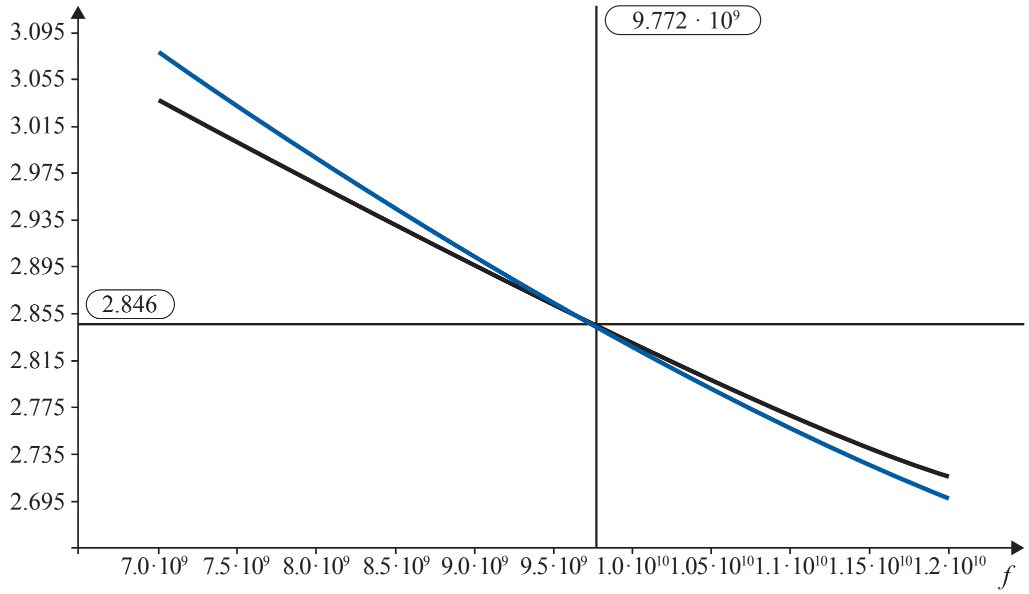

Fig. 1. Comparison of characteristics (1) (blue line) and (2) (black line) with $a = 3.2$ for texolite. Horizontal and vertical cross – frequency $f_{rel} = f_E$

3. Results

Figure 2 shows the simulation results for a rectangular waveguide. Some conclusions have to be made prior the comparison of it with the experimental results. According to the data obtained in [5], the frequency dependence of the reflection coefficient for the metal sphere is thoroughly described by analytical and semi-analytical expressions. The main difference between algorithm [12] and [5] is that the second demonstrates the characteristic nonlinearity of the function, with a similar dynamic of its increase. Numerical simulation confirms that the function is not linear and has a local minimum on the microwave.

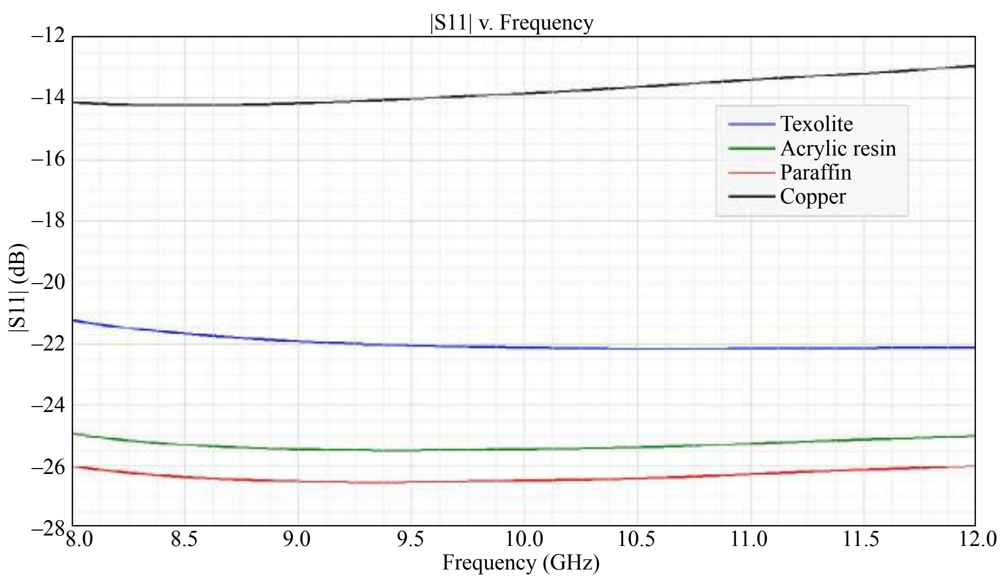

Fig. 2. Simulation results for the spheres in rectangular waveguide

Fundamentally different dynamics of the function is for a composite material sphere. The function $|S_{11}|(f)$ decreases with increasing frequency. This is obviously due to a change in the refraction index, in accordance to the characteristic on fig. 1.

The dynamics of functions for simple materials (such as acrylic resin and paraffin) visually completely coincide, merely the magnitude is different. Moreover, the increase in functions with increasing frequency is much slower than for the metal sphere.

In this context, it should be pointed out that increasing the function with increasing frequency for simple materials is a direct consequence of improving its discernibility effect in the waveguide. The data is confirmed in the paper [6].

Figures 3–6 show the comparison of numerical and experimental data for all samples in a rectangular waveguide. Here it is necessary to specify the method of analysis and obtaining experimental curves. Points for receiving system status reports are marked with red crosses. The smooth function is constructed using spline interpolation. It should be emphasized that the data between two points, the distance between which more than 0.5 GHz may be fundamentally different. There are two main reasons for this:

1. The first is a non-single-wave mode of operation in which the waveguide operates in the experiment (fundamentally not achievable).

2. The second is not a monochrome signal from the generator in the experiment (fundamentally not achievable).

The study [7] demonstrates that the experimental characteristics are experiencing strong oscillations. The reasons for this are given above. However, this paper presents raw data that should be processed in a specific way. The development of the algorithm for processing this data is a separate study. In this paper a simple algorithm for sampling reliable values at points tending to a function obtained by a numerical method is used. The quality of validation, foremost, has be established by the number of such points, and to a lesser extent than by its proximity to the reference function.

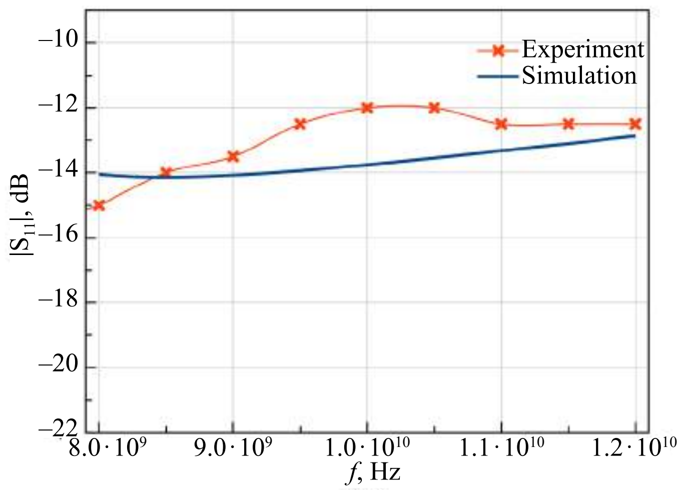

Fig. 3. Comparison of experimental data and simulation results for the copper sphere in rectangular waveguide

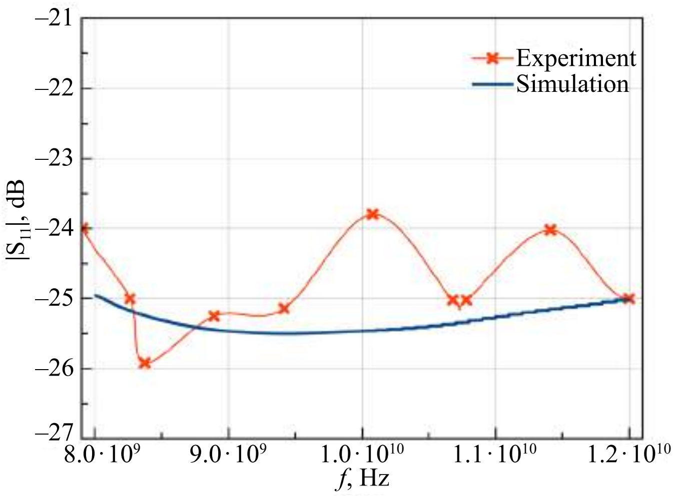

Fig. 4. Comparison of experimental data and simulation results for the acrylic resin sphere in rectangular waveguide

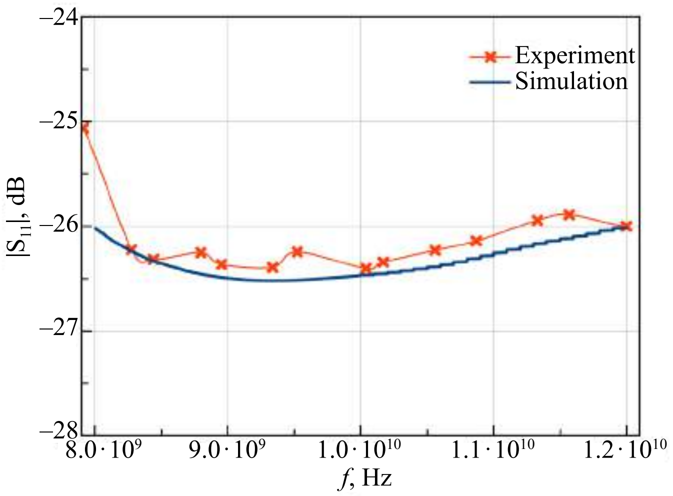

Fig. 5. Comparison of experimental data and simulation results for the paraffin sphere in rectangular waveguide

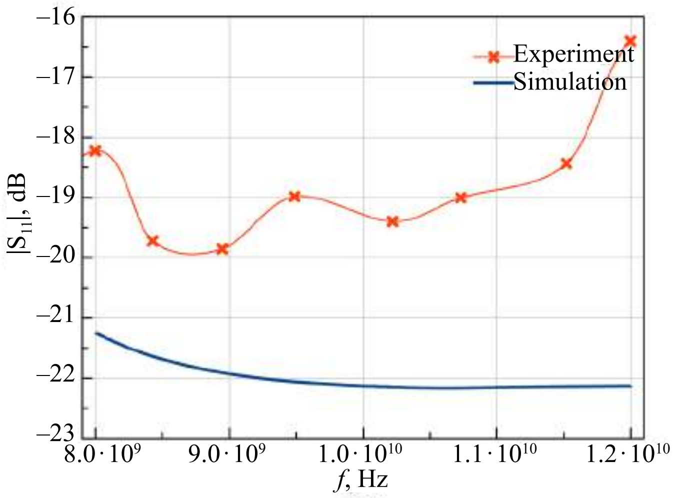

Fig. 6. Comparison of experimental data and simulation results for the texolite sphere in rectangular waveguide

Figure 7 shows the results of modeling the reflection coefficient for spheres in a circular waveguide. The magnitude of the expected value has decreased – this is due to the larger cross-sectional area of the circular waveguide. Characteristics have a clear oscillation. Nevertheless, the general dynamics of the functions is preserved (if we compare the starting and ending points of the analysis), in fig. 2. It is possible to conclude in this context that the resonance curve for a sphere in a closed space is more quickly and clearly observed in a circular waveguide but not in a rectangular one.

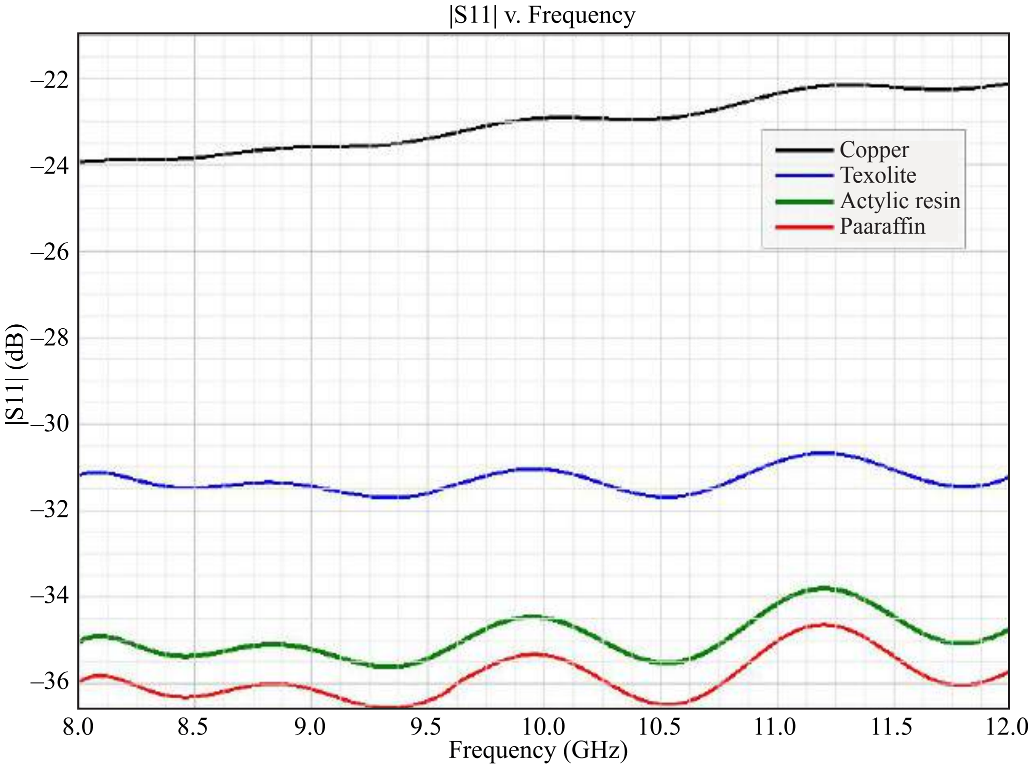

Fig. 7. Simulation results for the spheres in circular waveguide

Conclusion

A number of important conclusions are obtained in the paper. Clear correlation is indicated in comparison of simulation data for rectangular and circular waveguides. It is assumed that an effective analysis of inhomogeneities in the transmission line is necessary to analyze its electrophysical properties in different analysis systems. The experimental verification is implemented only for a rectangular waveguide in this paper. A similar experiment with spheres in a circular waveguide gives similar results, keeping the principle of causality.

Analyzing the characteristics for the metal sphere (fig. 3) the following conclusions are made [5; 6; 12]. Valuable results are obtained in accordance to dielectric spheres. The best data verification is found for paraffin (fig. 5). It may be due to the possibility of its accurate measurement in a preliminary experiment. The worst verification is maintained for the composite material (fig. 6). No matching points are found during the comparison. This verification is considered undergone due to the complexity of the description of the material parameters, as well as their experimental study. The intermediate value for the quality of verification is demonstrated by the acrylic resin sphere (fig. 4). It may be explained by the simulation of the magnetic conditions of the vacuum is not justified, but more accurate data on this sample has not been measured.

In this context, the development of a validated method for processing experimental data to reconstruct the electrophysical parameters of heterogeneity in the transmission line is a priority task of this study.

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