DOI: https://doi.org/10.15407/rpra27.02.140
UDC 621.373.826

I.V. Ivanchenko [1], V.A. Plakhtii [2], N.A. Popenko [1], and M.M. Khruslov [1, 2]

[1] O.Ya. Usikov Institute for Radiophysics and Electronics of NASU
12, Acad. Proskury St., Kharkiv, 61085, Ukraine
E-mail: khruslov.maksym@gmail.com
[2] V.N. Karazin National University of Kharkiv
4, Svobody Sq., Kharkiv, 61022, Ukraine

RESONANCE PROPERTIES OF AN X-BAND RECTANGULAR WAVEGUIDE SECTION WITH AN INHOMOGENEOUS DIELECTRIC INSET

Subject and Purpose. *In modern dielectrometry, the problem of detecting foreign inclusions in a radio-transparent material, which are significantly smaller than the operational wavelength, remains very important. The problem becomes even more complicated if it is required to determine complex permittivityof these inclusions. This work analyzes the conditions for the correct use of the original resonance method proposed by the authors earlier for determining permittivity of a local inclusion when its dimensions and dielectric constant change.*

Methods and Methodology. *The measured module consists of a rectangular X-band waveguide, which is partially filled with a dielectric in the form of a rectangular Teflon matrix with a local cubic inclusion inside. The dimensions of the matrix are fixed and are 23 mm × × 10 mm × 30 mm. Numerical modeling is performed using the Ansys HFSS software package. The dependences of the resonance frequencies of the module upon changing the dielectric constant of the cube are analyzed. The cube permittivity was changed between 3.8 and 100 in 5-unit steps. Permittivity of the material of the cube is determined by comparing arrays of calculated data with experimental results.*

Results. *Numerical modeling of the module was performed and its electrodynamic properties were determined in the frequency band of 8…10 GHz at different sizes and permittivity of the inclusion. For a cube with a facet size of 2 mm, the resonance frequency decreases with an permittivity increase of the material. For a cube with a facet size of 3 mm and permittivity above 50, additional resonances appear in the structure due to the excitation of resonant modes of the cube itself.*

Conclusion. *It has been shown that by varying the dielectric permittivity of the cubic inset between 3.8 and 100 it proves possible to provide for resonant mode excitation over the frequency range specified. This allows estimating the dielectric permittivity of the cubic inset's material by way of comparing the calculated versus measured data arrays concerning resonant frequency dependences upon material parameters.*

Keywords: *rectangular waveguide section, teflon matrix, local inclusion, resonance, permittivity.*

Introduction

The results of theoretical and experimental studies of the properties of a standard X-band rectangular waveguide with various inhomogeneities inside can be found in numerous scientific publications. Restricting ourselves by the problems of dielectrometry, we should emphasize the importance of both non-resonance and resonance methods of investi-

Citation: Ivanchenko, I.V., Plakhtii, V.A., Popenko, N.A., and Khruslov, M.M., 2022. Resonance Properties of an X-Band Rectangular Waveguide Section with an Inhomogeneous Dielectric Inset. *Radio Physics and Radio Astronomy*, **27**(2), pp. 140—144. https://doi.org/ 10.15407/rpra27.02.140

Цитування: Іванченко І.В., Плахтій В.А., Попенко Н.О., Хруслов М.М. Резонансні властивості секції прямокутного хвилеводу X-діапазону з неоднорідним діелектриком всередині. *Радіофізика і радіоастрономія.* 2022. Т. 27. № 2. С. 140—144. https://doi.org/10.15407/rpra27.02.140

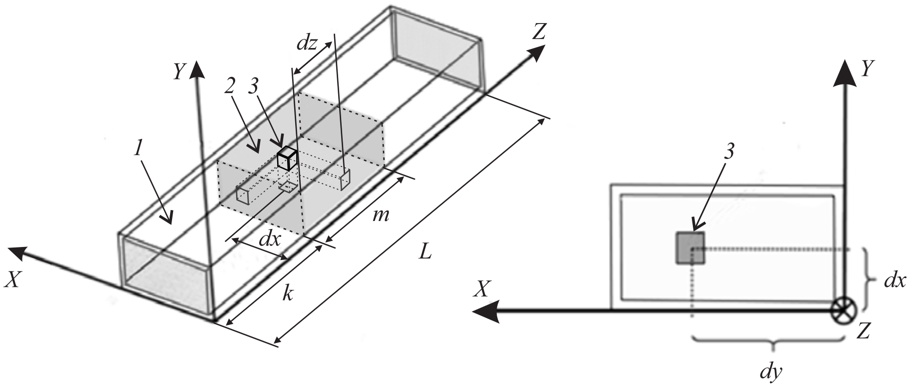


Fig. 1. Geometry of the structure

gation. As far as non-resonance methods are concerned, the task of determining the complex permittivity of various materials largely depends on availability of efficient solution techniques for inverse scattering problems [1, 2]. Of particular interest is the problem of detecting various foreign inclusions in dielectric insets of a significantly smaller size than the operating wavelength. The problem appears even more complicated if it is required not only to detect such an inclusion, but also to determine its complex dielectric permittivity [3, 4]. A description of our proposed method for determining the complex permittivity of a local inclusion within a teflon sample placed in a standard rectangular X-band waveguide is given in paper [5].

Among the resonance methods suitable for dielectric permittivity measurements, the cavity perturbation technique is particularly well known [6—11]. With the use of this method, the permittivity and the loss tangent of the sample under test can be determined from variations in the resonance frequency and Q-factor of the resonant cavity [12, 13]. In contrast to the case of dielectric resonator [14], the cavity perturbation technique does not impose strict requirements as to the shape and size of the sample under study. Still, the sample size should be selected so as to meet the recommendation of paper [15], namely that “the resonance frequency shift [shall] not exceed 5%.”

A novel resonance method for determining the complex dielectric permittivity of a local inclusion inside a teflon matrix of rectangular geometry was proposed in our paper [16]. A distinctive feature of the method is that the local inclusion under study also serves as a lumped element for exciting resonant modes in the “waveguide—matrix—inclusion” microwave module. It should be emphasized that “the method allows determining the permittivity and the loss angle tangent with errors within 0.1% and 5.0%, respectively” [16]. Further studies relating to numerical simulations of the structure showed that “the resonance appears at a certain frequency belonging to the band 8…11 GHz” [17].

In this paper the resonance method of paper [16] is extended further. The conditions for exciting a resonance in the “waveguide—matrix—inclusion” structure through varying the size and permittivity of the inset of cubic geometry are analyzed.

1. Model of the structure

The structure under tests (see Fig. 1) consisted of a standard rectangular X-band waveguide *1* (of length $L = 100$ mm) containing a teflon matrix *2* in the form of a parallelepiped, and a localized inset *3* in the form of a cube.

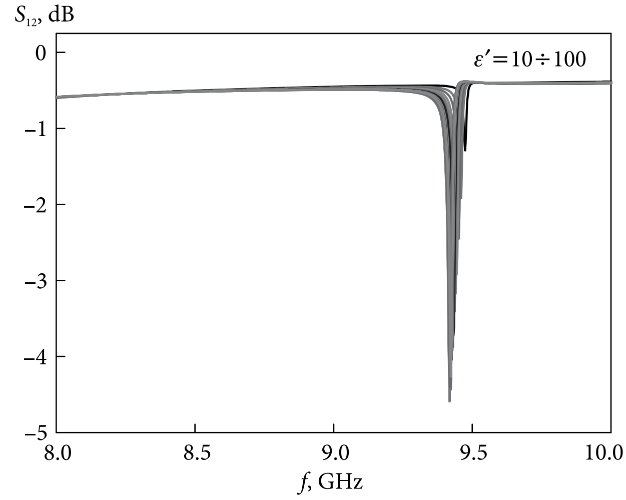


Fig. 2. The frequency dependence of the S_{12} ratio in the case of a cube with facet size 2 mm × 2 mm

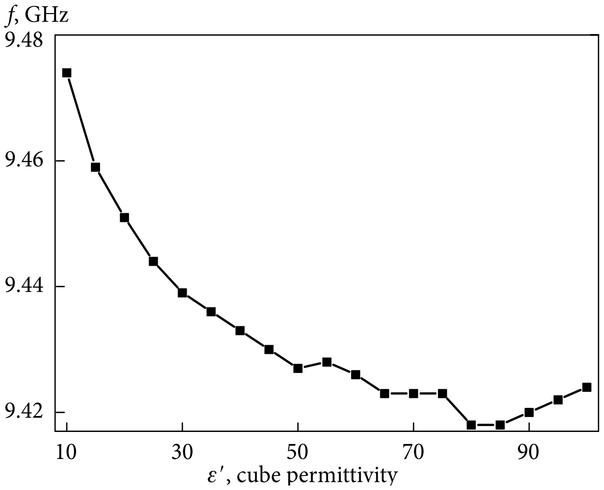


Fig. 3. Resonance frequency versus dielectric permittivity of the cube's material (2 mm × 2 mm cube's facet size)

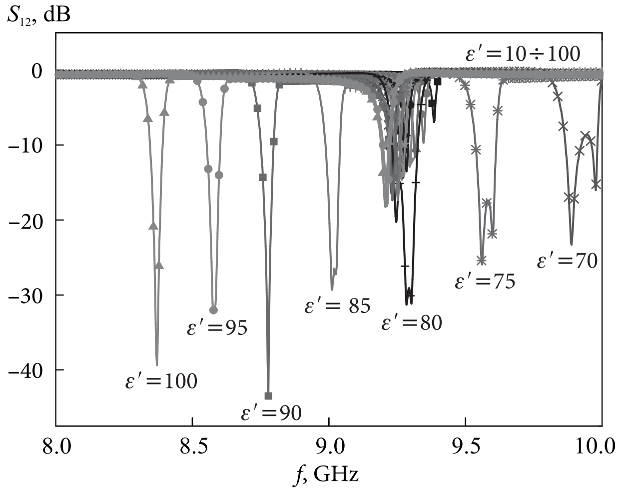


Fig. 4. The frequency dependence of the S_{12} parameter in the case of a cube with facet size of 3 mm × 3 mm

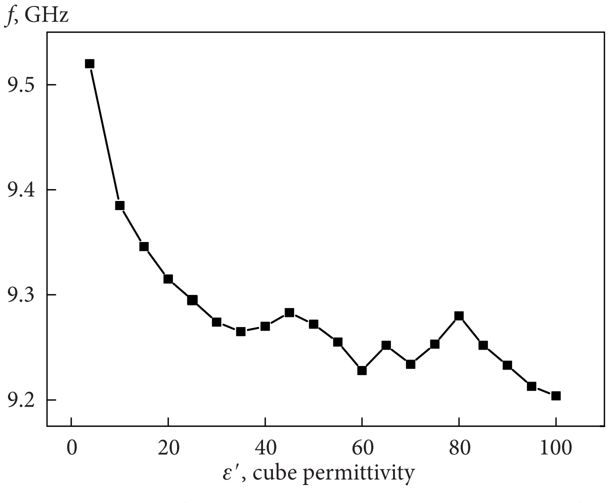


Fig. 5. Resonance frequency versus dielectric permittivity of the cubic inset (facet size 3 mm × 3 mm)

Numerical simulations of this structure, fed via "wave ports" wp1 and wp2, were performed with the use of the Ansys HFSS software package. The dependences shown by the resonance frequencies of the wave modes identified were analyzed for a variety of sizes and dielectric permittivities of the cubic inset. The matrix dimensions were fixed as 23 mm × 10 mm × 30 mm. In this paper, we present the results concerning the "waveguide — matrix — cubic inset" structure with facet sizes of the cube equal to 2 mm × 2 mm and 3 mm × 3 mm. The dielectric permittivity of the inset material was varied from 3.8 to 100 in 5-unit steps.

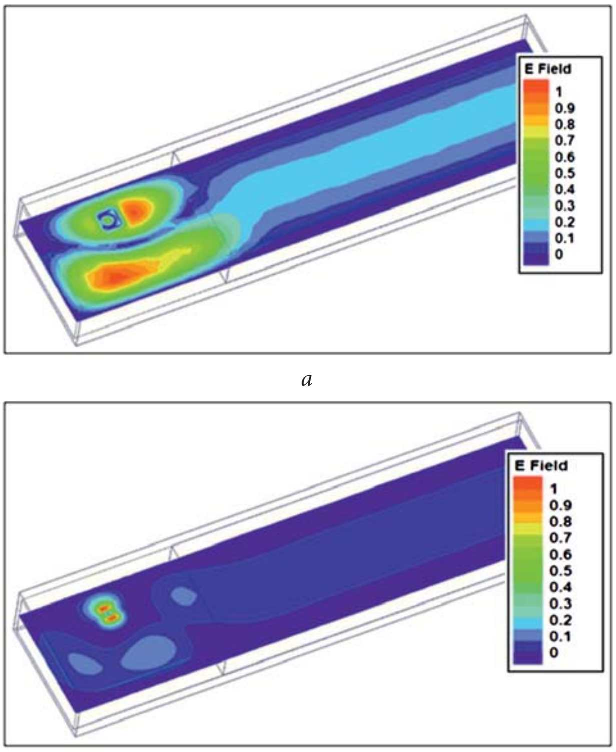
2. Results and analysis

We will analyze, before all, the frequency dependences shown by the transmission ratio S_{12} of signals traveling between the ports wp1 and wp2 (see Fig. 1), with a variety of the cube's permittivity values. The position of the cube (with facets of size 2 mm × 2 mm) within the matrix is defined by coordinates of its geometric center, specifically $dx = 18.75$ mm, $dy = 6$ mm, and $dz = 15$ mm (Fig. 1). In what follows, we will focus on analyzing the fundamental mode of the rectangular metal waveguide.

We have made a search for resonance frequencies over the range 8 GHz $< f <$ 10 GHz for a variety of dielectric permittivities ε' of the cube's material ranging from 10 to 100. The resonances have been found to concentrate in the narrower range, like 9.22 GHz $< f <$ 9.53 GHz (Fig. 2). Next, the resonance frequency of a mode that has been excited decreases almost exponentially as the cube's permittivity is increased, up to $\varepsilon' \approx 50$ (Fig. 3). With a further increase in the dielectric permittivity of the inset material, the resonance frequency varies in a non-monotonic way.

As the size of the cube is increased to 3 mm × × 3 mm × 3 mm, the frequency dependence of S_{12} becomes more complicated. One can observe a set of additional resonances through the operational frequency range (Fig. 4).

As the dielectric permittivity of the cube's material is increased, the resonance frequency of the excited mode decreases monotonically up to the point $\varepsilon' = 35$ (see Fig. 5). Further on, the frequency demonstrates a non-monotonic run versus ε', up to $\varepsilon' = 85$. With $\varepsilon' > 85$ the resonance frequency demonstrates again a nearly exponential decay with a growth in permittivity.



a

b

Fig. 6. Spatial field distributions of the total *E*-field at the frequency $f = 9.205$ GHz (*a*) and at $f = 9.945$ GHz (*b*) (the dielectric permittivity is $\varepsilon' = 70$)

To understand the reasons for the appearance of these additional resonances, we have analyzed spatial field distributions of the modes excited. When the permittivity of the cubic inset grows up, reaching values in the vicinity $\varepsilon' \le 50$, the electric field remains concentrated inside the teflon matrix, showing two amplitude variations along the *Ox* axis and one along the *Oz* axis (Fig. 6*a*). These field distributions can be interpreted as signatures of some resonance mode excited in the “waveguide—matrix—cube” structure. At still higher magnitudes of the cube’s dielectric permittivity ($\varepsilon' > 50$) one can observe more resonance frequencies to appear in the spectrum (Fig. 4). Analysis of the field strength’s spatial distributions associated with these new resonances shows the correspondent electromagnetic fields to be concentrated inside the cube. This suggests that the new modes are not eigenwaves of the entire “waveguide—matrix—cube” structure, but rather modes of the cubic dielectric resonator sitting inside the dielectric matrix. As an example, a spatial field distribution corresponding to $f = 9.945$ GHz is shown in Fig. 6*b* for a cube with material permittivity $\varepsilon' = 70$ and facet size 3 mm × 3 mm.

Conclusions

Numerical simulations of the “waveguide—matrix—cube” structure have been carried out and the possible resonances studied over a 8 to 10 GHz frequency range, for a variety of sizes and dielectric permittivities of the cubic inset. In the case of a cube having facets of size 2 mm × 2 mm the modal frequency decreases as the dielectric permittivity of the cube’s material is increased. In the case of a cube with facets 3 mm × 3 mm in size and $\varepsilon' > 50$, the spatial field distributions correspond both to the resonances where the electric field component is concentrated mainly in the teflon matrix, and to modes of the cubic dielectric resonator (with different sets of field configurations in the cube).

When the cube permittivity is changed from 3.8 to 100, resonance wave modes are excited in the frequency range analyzed. Accordingly, it is possible, in all cases, to evaluate the dielectric permittivity of the inset material by comparing arrays of calculated data with corresponding measured results [16].

REFERENCES

1. Gragnani, G.L., 2010. Shape reconstruction of 2-D dielectric objects by an analytical method. *Int’l. J. Signal and Imaging Syst. Eng.*, **3**(2), pp. 81—92. DOI: 10.1504/IJSISE.2010.034997.
2. Smirnov, A.P., Semenov, A.N., and Shestopalov, Y.V., 2013. FDTD Simulation of Waveguide with Non-uniform Dielectric Slab. In: PIERS 2013 STOCKHOLM. *Progress in Electromagnetics Research Symposium.* Stockholm, Sweden, 12—15 Aug. 2013, pp. 76—83.
3. Smirnov, A.P., Sheina, E.A., Shestopalov, Y.V. and Semenov, A.N., 2015. Numerical simulation of a nonuniform dielectric inclusion in a waveguide aimed at reconstructing its permittivity. In: *2015 Int. Conf. Electromagnetics in Advanced Applications (ICEAA).* Torino, Italy, 7—11 Sept. 2015, pp. 419—421. DOI: 10.1109/ICEAA.2015.7297147.
4. Sheina, E.A., Smirnov, A.P. and Shestopalov, Y.V., 2016. Influence of standing waves on the solution of the inverse problem of reconstructing parameters of a dielectric inclusion in a waveguide. In: *2016 URSI Int. Symp. Electromagnetic Theory (EMTS).* Espoo, Finland, 14—18 Aug. 2016, pp. 643—646. DOI: 10.1109/URSI-EMTS.2016.7571479.
5. Ivanchenko, I., Khruslov, M., Popenko, N., Sheina, E., Smirnov, A. and Shestopalov,Y., 2016. Reconstructing complex permittivity of local inhomogeneites in a radio-transparent dielectric matrix located in a waveguide. In: *2016 22nd Int. Conf. Applied Electromagnetics and Communications (ICECOM).* Dubrovnik, Croatia, 19—21 Sept. 2016, pp. 1—3. DOI: 10.1109/ICECom.2016.7843882.

6. Carter, R.G., 2001. Accuracy of microwave cavity perturbation measurements. *IEEE Trans. Microwave Theory Tech.*, **49**(5), pp. 918—923. DOI: 10.1109/22.920149.
7. Sheen, J., 2005. Study of microwave dielectric properties measurements by various resonance techniques. *Measurement,* **37**(2), pp. 123—130. DOI: 10.1016/j.measurement.2004.11.006.
8. Kumar, A., Sharma, S. and Singh, G., 2007. Measurement of Dielectric Constant and Loss Factor of the Dielectric Material at Microwave Frequencies. *Prog. Electromagn. Res. (PIER)*, **69**, pp. 47—54. DOI: 10.2528/PIER06111204.
9. Balmus, S.-B., Pascariu, G.-N., Creanga, F., Dumitru, I. and Sandu, D.D., 2006. The cavity perturbation method for the measurement of the relative dielectric permittivity in the microwave range. *J. Optoelectron. Adv. Mater.*, **8**(3), pp. 971—977.
10. Sheen, J., 2007. Amendment of cavity perturbation technique for loss tangent measurement at microwave frequencies. *J. Appl. Phys.*, **102**(1), id. 014102. DOI: 10.1063/1.2751484.
11. Robinson, M.P., Fitton, L.C., Little, A., Cobb, S.N. and Ashby, S.P., 2019. Dielectric replica measurement: a new technique for obtaining the complex permittivity of irregularly shaped objects. *Meas. Sci. Technol.*, **30**(4), id. 045902. DOI: 10.1088/1361-6501/ab0466.
12. Dube, D.C., Lanagan, M.T., Kim, J.H. and Jang, S.J., 1988. Dielectric measurement on substrate materials at microwave frequencies using a cavity perturbation technique. *J. Appl. Phys.*, **63**(7), pp. 2466—2468. DOI: 10.1063/1.341024.
13. Sheen, J., 2005. Study of microwave dielectric properties measurements by various resonance techniques. *Measurement*, **37**(2), pp. 123—130. DOI: 10.1016/j.measurement.2004.11.006.
14. Hakki, B.W. and Coleman, P.D., 1960. A Dielectric Resonator Method of Measuring Inductive Capacities in the Millimeter Range. *IEEE Trans. Microwave Theory Tech.*, **8**(4), pp. 402—410. DOI: 10.1109/TMTT.1960.1124749.
15. Banerjee, P., Ghosh, G. and Biswas, S.K., 2010. Measurement of dielectric properties of medium loss samples at X-band frequencies. *J. Optoelectron. Adv. Mater.*, **12**(6), pp. 1367—1371.
16. Ivanchenko, I., Khruslov, M., Popenko, N., Plakhtii, V., Rönnow, D. and Shestopalov, Y., 2020. A novel resonance method for determining the complex permittivity of local inclusions in a rectangular waveguide. *Meas. Sci. Technol.*, **31**(9), id. 097001. DOI: 10.1088/1361-6501/ab870f.
17. Ivanchenko, I., Popenko, N., Khruslov, M. and Plakhtii, V., 2020 Numerical Smulations of the X-band Waveguide Partially Filled with a Dielectric with Local Iinhomogeneity Inside. In: *2020 IEEE Ukrainian Microwave Week (UkrMW).* Kharkiv, Ukraine, 21—25 Sept. 2020, pp. 688—691. DOI: 10.1109/UkrMW49653.2020.9252647.

Received 17.11.2021

І.В. Іванченко [1], В.А. Плахтій [2], Н.О. Попенко [1], М.М. Хруслов [1, 2]

[1] Інститут радіофізики та електроніки ім. О.Я. Усикова НАН України
12, вул. Акад. Проскури, Харків, 61085, Україна
E-mail: khruslov.maksym@gmail.com
[2] Харківський національний університет імені В.Н. Каразіна
4, майдан Свободи, Харків, 61022, Україна

РЕЗОНАНСНІ ВЛАСТИВОСТІ СЕКЦІЇ ПРЯМОКУТНОГО ХВИЛЕВОДУ Х-ДІАПАЗОНУ З НЕОДНОРІДНИМ ДІЕЛЕКТРИКОМ ВСЕРЕДИНІ

Предмет і мета роботи. У сучасній діелектрометрії залишається важливою проблема виявлення в радіопрозорому матеріалі сторонніх включень, що за розміром є значно меншими за робочу довжину хвилі. Задача стає ще складнішою, якщо потрібно визначити комплексну діелектричну проникність цих включень. У цій роботі аналізуються умови коректного використання запропонованого авторами раніше оригінального резонансного методу визначення комплексної діелектричної проникності локального включення при зміні його розмірів і діелектричної проникності.

Методи та методологія. Вимірювальний модуль складається з прямокутного хвилеводу Х-діапазону, який частково заповнений діелектриком у вигляді прямокутної тефлонової матриці з локальним включенням кубічної форми всередині. Розміри матриці фіксовані та становлять 23 мм × 10 мм × 30 мм. Числове моделювання виконується за допомогою програмного пакету Ansys HFSS. Аналізуються залежності резонансних частот модуля при зміні діелектричної проникності куба. Діелектрична проникність куба змінювалася від 3.8 до 100 з кроком 5 одиниць. Діелектрична проникність матеріалу куба визначається шляхом порівняння масивів розрахункових даних із результатами експерименту.

Результати. Виконано числове моделювання модуля та визначено його електродинамічні властивості у смузі частот 8…10 ГГц при різних розмірах і діелектричних проникностях включення. Для куба з розміром грані 2 мм резонансна частота зменшується зі збільшенням діелектричної проникності матеріалу. Для куба з розміром грані 3 мм і діелектричною проникністю вище 50 в структурі з'являються додаткові резонанси, що обумовлені збудженням резонансних мод самого куба.

Висновки. Показано, що використання запропонованого методу дозволяє визначати діелектричну проникність локального включення кубічної форми від 3.8 до 100.

Ключові слова: *прямокутний переріз хвилеводу, тефлонова матриця, локальне включення, резонанс, діелектрична проникність.*