Visnyk NTUU KPI Seriia – Radiotekhnika Radioaparatobuduvannia, 2019, Iss. 78, pp. 6–12

УДК 538.36.08

Method of Measuring Effective Dielectric Permittivity of Partially Filled Waveguides Using a Mismatched T-Bridge

Karashchuk N. M.[1], *Manoilov V. P.*[2], ✉*Sidorchuk O. L.*[1], *Tarasenko S. M.*[1], *Chukhov V. V.*[2]

[1]Zhytomyr military institute named after S. P. Korolyov
[2]Zhytomyr State Technological University

E-mail: *sidorchuk_o@ukr.net*

Introduction. Waveguides, partially filled with dielectric material (partially filled waveguides) are widely used in the super high frequency equipment. They have certain advantages over hollow waveguides, including the possibility of reducing sizes of a cross-section, increasing the power of radiation and suppressing undesired types of waves. Following the production of diverse new dielectric materials intended for use in super high frequency range devices, there is a need to continuously develop methods of calculation and measuring characteristics of partially filled waveguides.
Statement of the problem. The theory of completely filled waveguides and waveguides with dielectric filling along narrow walls is developed quite thoroughly. However, its application to various waveguide devices requires the solution of transcendental equations, which is possible only using numerical methods. This makes it difficult to obtain information about any characteristics of a device. For the study of partially filled waveguides with different sample height, among others, this paper presents an approach, which is based on the representation of the relative permittivity of the medium in the form of two real functions, each of which depends on the cross-section from one coordinate. The paper also introduces the method which allows calculating the propagation constant at any frequency, by measuring the value of effective dielectric permittivity.
Results and discussion. The results of the analysis shows that known methods of measuring effective dielectric permittivity have certain shortcomings in relation to the modification of partially filled waveguides, bandlimitedness, and a significant relative error of measurement with increasing effective dielectric permittivity. It is necessary to match the bridge at each frequency, reaching the absence of a signal in the arm E for identical loads that are connected to the side arm. For this, bridges have tuning elements in the form of pins, diaphragms, etc. The method for measuring effective dielectric permittivity of partially filled waveguides using an unmatched T-bridge, which does not have these deficiencies, is introduced.
Conclusions. The scientific novelty of the proposed method for measuring effective permittivity of partially filled waveguides using an unmatched T-bridge gives the possibility of providing broadbandness, increasing the accuracy of measurements, and the universality through the use of a panoramic indicator of the standing wave ratio using the voltage and electron-computer. The results obtained should be used when designing new antenna systems, which include partly filled waveguides, as well as part of teaching and learning activities for creating new workplaces or improving existing ones aimed at laboratory and practical training using the above method of measurement.

Key words: effective dielectric permittivity; partial dielectric filling; method for measuring effective dielectric permittivity; partially filled waveguide; teaching and learning activities

DOI: 10.20535/RADAP.2019.78.6-12

1 Statement of the problem

Waveguides, partially filled with dielectric material - partially filled waveguides (PFWs) - are widely used in the super high frequency (SHF) equipment [1–5]. The increased interest to such waveguides is due to the fact that they have a number of advantages over hollow waveguides. Thus, changing the form of their filling and dielectric permittivity of a material, it is possible to control the distribution of the power flow in a cross-section, the position of the circular polarization points of the SHF magnetic field, and other characteristics [6, 7]. This enables increasing the power of radiation and suppressing undesired types of waves in waveguides [9, 10].

At present, various dielectric materials are intended for the use in SHF range devices with small losses (with relative permittivity within $\varepsilon_r =$

$2\ldots20$). Improvement of waveguide characteristics with frequency dielectric filling goes along with a decrease in their size and greater stability of characteristics in the frequency range, which is the basis for the creation of small size and broadband antennas [10, 12].

Thus, PFWs are widely used in various SHF devices. Therefore, there is a need to continuously develop methods of calculation and measuring their characteristics.

2 Analysis of recent research and publications

The number of dielectrics that are used in the super high frequency (SHF) equipment is rapidly increasing now. The emergence of new dielectrics contributes to the creation of new transmission lines and SHF devices, such as partially filled waveguides (PFWs), resonators, filters, phase shifters, etc. The practical application of such devices without reference to their dielectric permittivities is impossible.

The electrodynamic problem solving for PFW reduces to finding the propagation constant in the waveguide [13,14]. The exact solution of the Helmholtz equation of the electromagnetic field for PFW is only possible in certain cases, for example, in layered waveguides, when the distribution limit is subject to the piecewise continuous law of the distribution of permittivities. The classical methods for determining the propagation constants in PFW are reduced to solving the dispersion equation obtained either by comparing the tangential components of the electric and magnetic fields at the distribution limits of each layer, or by the theory of circles [15, 16].

In [14], for the study of PFWs with different sample height, an approach, based on the representation of the relative permittivity of the medium in the form of two real-valued functions, each of which depends in the cross-section from one coordinate, is introduced. This is an approximate method for determining proper scalar and vector functions of a PFW. At first, the approximation of the piecewise-inhomogeneous waveguide filling allowed the authors to reduce the problem to the Hill equation. Given only one member in these series, the solution of the problem was obtained in Mathieu functions.

Any theory needs to be practically confirmed. This can be a full-scale experiment (measurement) or a computer simulation with the help of modern software packages.

Measurements of effective dielectric permittivity are considered in many papers [13,14]. In [9], a method for measuring effective dielectric permittivity ε by a measuring line was introduced. One of the advantages of the method is its simplicity, and, among the disadvantages, there is the ability to use only those modifications of PFWs that do not interfere with the movement of a measuring line probe.

The studies [16,17] show that at extreme frequencies of the standing-wave ratio (SWR) characteristics on a panoramic indicator screen there is the possibility to fulfill the following condition:

$$\beta\ell = x\frac{\pi}{2}, \tag{1}$$

where β - the wave number in the waveguide; ℓ - the length of the dielectric sample; $x = 2n$ - at the point of minimum and $x = 2n + 1$ at the point of maximum, $n = 1, 2, 3 \ldots$.

The condition (1) is equivalent to the fact that along the sample of the dielectric that is being investigated, an integer of half-waves is inserted:

$$\ell = n\frac{\lambda}{2}, \tag{2}$$

where λ is the wavelength in the waveguide with the dielectric that is being investigated, or, equivalently, the even number of quarters of the wavelengths:

$$\ell = 2n\frac{\lambda}{4}. \tag{3}$$

The condition (1) can be rewritten in the following form:

$$\ell = 2n\frac{\pi}{2}. \tag{4}$$

In [18], for analysis of reflection coefficient it is shown that the following condition is fulfilled at the maxima frequencies:

$$\beta\ell = (2n + 1)\,\frac{\pi}{2}, \tag{5}$$

that is, along the dielectric sample, an odd number of quarters of wavelengths is inserted:

$$\beta\ell = (2n + 1)\,\frac{\lambda}{4}. \tag{6}$$

Consequently, in the general case, the conditions of extremums can be rewritten in the form:

$$\beta\ell = x\frac{\pi}{2}, \tag{7}$$

where $x = 2n$ is at the point of minimum and $x = 2n+1$ is at the point of maximum.

Thus, conditions (1) and (2) have a clear physical content, the frequency of the minimum is a resonant frequency, and the frequency of the maximum is the antiresonance frequency.

As the result of the measurement, the condition (7) is fulfilled, then one measured extremum frequency is not enough, but it is still necessary to know the number of half waves (quarter waves) that are enclosed along the sample - n.

For this, condition (7) can be written in the form analogous to the system as relating to ε_r, then for a completely filled waveguide [17, 18]:

$$\frac{n_0^2 \lambda_0^2}{\varepsilon - \left(\frac{\lambda_0}{2a}\right)^2} = 4\ell^2, \tag{8}$$

$$\frac{\left(n_0 + q\right)^2 \lambda_0^2}{\varepsilon - \left(\frac{\lambda}{2a}\right)^2} = 4\ell^2, \tag{9}$$

where a is the size of the broad wall of the waveguide; λ_0 – wavelength of the generator; λ – wavelength in the dielectric. For this it is believed that $\varepsilon\left(f_0\right) = \varepsilon\left(f\right) = \varepsilon$; q – a number of half-waves along dielectrics.

For the measurement of the frequency characteristic of SWR – $K_c\left(f\right)$ in [17, 18], a measuring device was developed on the basis of a panoramic indicator of SWR, and the equations (8), (9) were solved as follows:

$$n_0 = q + \sqrt{\left(qA\right)^2 - \left(\ell/a\ \right)^2\left(A^2 - 1\right)}, \tag{10}$$

$$\varepsilon = \left(\frac{\lambda_0}{2}\right)^2 \left[\left(1/\ \right) + \left(\frac{n_0}{\ell}\right)^2\right], \tag{11}$$

where $A = f/f_0$.

In fig. 1, the dependences of the magnitude $\sqrt{\varepsilon}$ on the decay factor for the waveguide with two plates, respectively, at the different filling t_x for the values $a/\lambda\ = 0,6$ and $a/\lambda\ = 0,7$ calculated by the expressions (10) and (11), are given. If a certain curve does not reach the value $\sqrt{\varepsilon} \approx 3,5$, this means that at given t_x higher-order modes may occur in a rectangular waveguide.

All dependencies are developed for such values of t_x, when only the wave of the main type (H_{10}) is applied to PFW.

In order to reduce the reflection from the output ends of the dielectric plates, it is proposed to use the cutoffs, and the presence of higher-order modes can be detected with the help of the standing wave pattern.

Thus, by measuring the value of effective dielectric permittivity ε, it's possible to calculate the propagation constant at any frequency. As the magnitude ε increases, the deceleration rate m increases as well and its value approaches $\sqrt{\varepsilon}$. As the size of the filling as well as the effective dielectric permittivity ε increase, and the value of a/λ decreases, the propagation of the main wave in the PFW becomes possible.

The waveguide width, normalized to the wavelength, depending on the filling, changes more rapidly with small fillings. The conducted experimental studies of measuring ε with the help of a panoramic indicator of the voltage standing-wave ratio (VSWR) have proved that the relative error of measurement for dielectric permittivity $\varepsilon \leq 2$ does not exceed ±2% in the frequency range (26 - 37,5) GHz.

The use of a panoramic indicator of VSWR in the case where the partial dielectric filling (PDF) has a relative effective dielectric permittivity that changes within the limits $\varepsilon = 5 \ldots 15$ has a relative measurement error ±15%, which is a disadvantage of this method [20].

Therefore, **the purpose of the paper** is to develop the method for measuring the effective dielectric permittivity of a PFW in order to improve the accuracy of measuring ε.

3 Results

In order to increase the accuracy of measuring ε of a PFW, it is proposed to apply a bridge measurement method based on the waveguide bridge [10].

The method of using bridge meters is to compare the unknown impedance of a SHF device with the reference one. Therefore, the reference impedance is a necessary part of a bridge meter. Various bridge coaxial and waveguide circuits are known. Consider one of them - the waveguide bridge [10] (fig. 2).

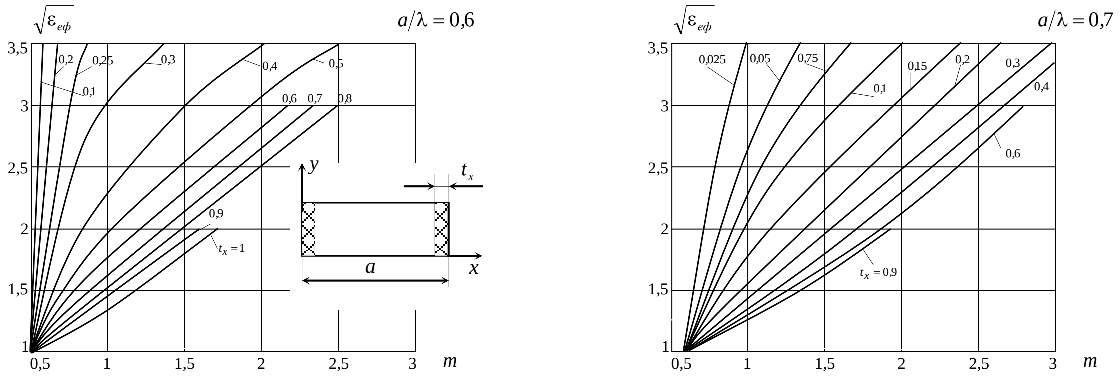
The wave from the SHF generator comes in the 4th bridge arm. If the bridge is strictly symmetrical (agreed), the wave is divided in half between arms 1 and 2 and does not pass in the arm 3 to which the detector and the indicator are connected. If the reference impedance (standard measure) is connected to the arm 1, the bridge will only be matched if the impedance (load), equal to the reference one, is connected to the arm 2. At that, the waves, reflected from both loads, at the input of the arm 3 are completely subtracted. In all other cases, if the module or phase of the reflection coefficient of the load in the arm 2 differs from the module or phase of the reflection coefficient of the standard measure, and a wave that is proportional to the difference between the amplitudes and phases of waves reflected from both loads will appear in the arm 3.

Thus, with the help of a bridge, one can estimate the difference between the impedances of two loads.

For graduation, it is possible to connect sequentially several loads with known VSWR to the arm 2, observed the indicator readings; and then mark the whole scale according to the keys received.

The disadvantage of bridge indicators is the very narrow frequency range at which the bridge remains matched. In practice, it is necessary to match the bridge at each frequency, reaching the absence of a signal in the arm 3 with the same loads that are connected to the arms 1 and 2. For this bridge there are adjusting elements in the form of pins, diaphragms, etc. Sometimes matching transformers, which are activated between the inputs of the arms 1 and 2 and the loads, are used for adjusting.

In some cases, it is possible to exclude this procedure by applying a method of using a mismatched bridge to compare impedances, which is widely used in practice [20].



(a) (b)

Fig. 1. The relationship between ε and m

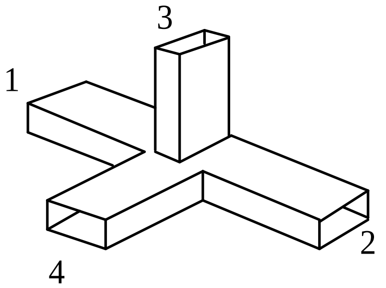


Fig. 2. Scheme of a waveguide bridge

Consider the method of measuring the parameters of SHF devices, consisting of a VSWR panoramic indicator and a mismatched bridge.

The composition of the diagram of measuring VSWR of partially filled waveguides by a computer includes:

OFG - oscillation frequency generator;

D1 - direct-reading incident wave detector;

D2 - direct-reading standing wave detector;

ID - interface device;

T - hybrid-t;

ECM - electronic computing machine;

I - indicator.

The measurement method is as follows: the reference load 7 is connected to the arm 2 (fig. 3), to the arm 1 – the special load 6 with reflection coefficient varying in module and phase (the oscillator 5 is connected to the arm 4). With the help of the adjustment controls of this load, zero indicator readings are achieved. For this, the sum of the waves in the arm 3 due to the asymmetry of the hybrid-t, the reflection in it and from its flanges, and the reflection from the reference and regulated loads, equals to zero. If a short-circuited waveguide with PDF is connected to the arm 2, then the magnitude of the reflection coefficient of the waveguide with PDF can be found by moving a short-circuiting switch.

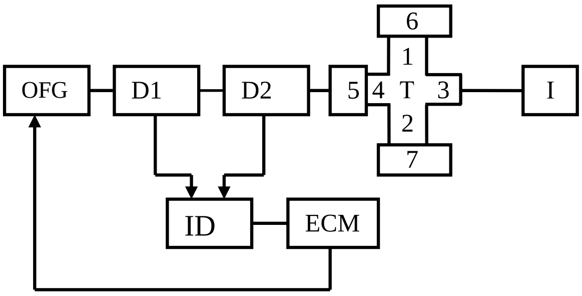


Fig. 3. The block diagram of measuring VSWR of partially filled waveguides by a computer

In this device, the detected signals from the detectors of the directional couplers of the incident D1 and the reflected D2 waves instead of the panoramic indicator PI are fed to the interface device ID where they are amplified and converted into binary code. The basis of the oscillation frequency generator of such a device most typically is a digital frequency synthesizer controlled by its computer. Since the accuracy of frequency synthesizers is constantly improving, in such a panoramic indicator there is no need to use an external frequency meter.

The functions of displaying, controlling oscillator frequency generator and calculating are performed by a personal computer.

The results of measurements can be automatically generated in the form of a report, for example, in MS Excel format.

Fig. 4 shows the dependencies of the value ε on the ratio t_x/a , calculated from the expressions (10) and (11) and measured experimentally by the proposed method based on a mismatched bridge (where n is the motion distance of a short-circuiting switch).

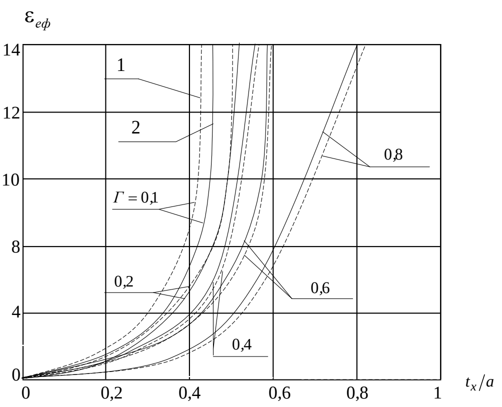


Fig. 4. Dependence of the waveguide with two dielectric plates adjacent to the walls of the waveguide (1 - experiment, 2 - measurement)

The transition from the reflection coefficient of the PFW to SWR can be carried out either according to the known formula [7,18] or according to the diagram [9].

The use of the expressions (10) and (11) for calculation allows determining ε of the PFW, and the use of a bridge meter allows precise measuring ε in the required frequency band. The calculation and experimental studies conducted for a waveguide with two plates for ε have a little variation between the curves. The relative error for the dielectric permittivity $\varepsilon \leq 15$ does not exceed $\pm 0,7\%$ in the range (26 - 37.5) GHz.

The proposed method with the use of a bridge, in which measure is a controlled short-circuiting switch, is widely used to measure dielectric properties of materials, since compared with other methods in many practical cases, it is relatively simpler and more universally applicable for preparing and conducting measurements.

Conclusions

Consequently, as a result of the conducted research, a method for measuring the effective dielectric permittivity of a PFW with the help of a mismatched T-bridge with increased accuracy of measurement of ε is proposed.

An expression ε for the effective dielectric permittivity of a partially filled waveguide is obtained. The curves of the dependence of effective dielectric permittivity on the slowness factor $\sqrt{\varepsilon}\,(m)$ for a waveguide with two dielectric plates with a different value of filling factor t_x for fixed electric sizes of the cross section of a rectangular waveguide a/λ for the condition of propagation of the wave of the main type (H_{10}) are given.

The graphs obtained by the expressions derived for the measuring unit on the basis of the panoramic indicator of the standing wave ratio give an opportunity to analyze the effect of waveguide filling, taking into account their effective dielectric permittivity, on the change of their cross-section sizes and the type of waves in a waveguide. The relative error of measurement for effective dielectric permittivity $\varepsilon \leq 2$ did not exceed $\pm 2\%$ in the frequency range (26 - 37.5) GHz according to the results of experimental measurements.

Thus, a more precise method of measuring the effective dielectric permittivity of a PFW in the frequency range based on the application of a mismatched T-bridge has been developed.

An electron-computer was used to increase the efficiency of measuring the effective dielectric permittivity of a PFW.

The calculated and experimental curves of the dependences of the effective dielectric permittivity on the location of the plates in the waveguide $\varepsilon\ (t_x/a\ )$ are given. The relative error for the dielectric permittivity $\varepsilon \leq 15$ does not exceed $\pm 0,7\%$ in the frequency range (26 - 37.5) GHz.

The advantage of the proposed measurement method is the use of a personal computer that controls the oscillation frequency generator, performs calculations and displays their results on the monitor. This increases the flexibility of the use of the device to measure VSWR of a PFW with acomputer and decreases the risk of its obsolete depreciation.

The software of such a device allows receiving dependencies of measurement parameters on frequency or power, filtering them, carrying out statistical processing with different software-installed parameters, identifying characteristic points on the graphs (for example, search of the minima and maxima required in this case) and calculating other derivative parameters [13–16].

The results of measurements can be automatically generated in the form of a report, for example, in MS Excel format. Moreover, in some of these devices, the software interface is open and documented.

The scientific novelty of the proposed method for measuring the effective dielectric permittivity of a PFW with the help of a mismatched T-bridge is the ability to provide broadbandness, increase the accuracy of measurements, universality through the use of a panoramic indicator of the PFW and a computer. One more distinguishing feature of this method is the ability to measure effective dielectric permittivity of such a PFW, where other measurement methods are not suitable.

The results obtained should be used during the design of new antenna systems, which include a PFW, as well as in the learning process in order to create new or improve existing environment for laboratory and practical training using the above method of measurement.

References

[1] Chernishov P., Samsonov V.P. and Chernishov M.P. (2006) *Tekhnichna elektrodinamika* [Technical electrodynamics]. Kharkiv: NTU "KhPI 290 p.

[2] Kolomeytsev V.A., Komarov V.V. and Khomyakov S.V. (2000) Ridged waveguides with thin dielectric slabs. *Microwave and Optical Technology Letters*, Vol. 25, Iss. 6, pp. 419-423. DOI: 10.1002/(sici)1098-2760(20000620)25:6<419::aid-mop16>3.0.co;2-7

[3] Ando M., Hirokawa J., Yamamoto T., Akiyama A., Kimura Y. and Goto N. (1998) Novel single-layer waveguides for high-efficiency millimeter-wave arrays. *IEEE Transactions on Microwave Theory and Techniques*, Vol. 46, Iss. 6, pp. 792-799. DOI: 10.1109/22.681202

[4] Scott M.M. and Faircloth D.L. (2013) Microwave Permittivity Determination for Materials With Out-of-Plane and Off-Diagonal Dielectric Anisotropy. *IEEE Transactions on Microwave Theory and Techniques*, Vol. 61, Iss. 6, pp. 2471-2480. DOI: 10.1109/tmtt.2013.2260169

[5] Wang W., Zhong S., Zhang Y. and Liang X. (2006) A Broadband Slotted Ridge Waveguide Antenna Array. *IEEE Transactions on Antennas and Propagation*, Vol. 54, Iss. 8, pp. 2416-2420. DOI: 10.1109/tap.2006.879216

[6] Krenitsky A. P. and Meshchanov V. P. (2001) *Sverkhshirokopolosnyye mikrovolnovyye ustroystva* [Ultra-wideband microwave devices]. Moscow, Radio and Communications, 554 p.

[7] Neganov V.A., Klyuev D.S. and Tabakov D.P. (2015) *Ustroystva SVCH i antenny* [Microwave devices and antennas]. Moscow, 724 p.

[8] Somov A.M. and Kabetov R.V. (2016) *Proyektirovaniye antenno-fidernykh ustroystv* [Designing antenna-feeder devices]. Moscow, Hotline-Telecom, 282 p.

[9] Kuraev A. A., Popkova T. L. and Sinitsyn A. K. (2004) *Electrodynamics and radio wave propagation* [Elektrodinamika i rasprostraneniye radiovoln], Minsk, Bestprint, 357 p.

[10] Orfanidis S. J. (2008) *Electromagnetic Waves and Antennas* Textbook, Rutgers University, 819 p.

[11] Karashchuk N. M., Manoylov V. P., Friez S. P. and Chukhov V. V. (2018) Investigation of the influence of partial dielectric filling on the dimensions of a rectangular waveguide [Doslidzhennya vplyvu chastkovoho dielektrychnoho zapovnennya na rozmiry pryamokutnoho khvylevodu], *Problems of creation, testing, application and operation of complex information systems*, Vol. 15, pp. 103-117.

[12] Pochernyaev V.N. and Tsibizov K.N. (2003) *Teoriya slozhnykh volnovodov* [The Theory of Complicated Waveguides] Kyiv: Naukoviy St. 224 p.

[13] Abdullin R.R. and Sokolov R.I. (2016) Experimental research of leaky-wave antenna based on covered rectangular waveguide with transverse slots. *2016 URSI Asia-Pacific Radio Science Conference (URSI AP-RASC)*, . DOI: 10.1109/ursiap-rasc.2016.7601153

[14] Pochernyaev V.N. and Skrypnik L.V. (1990) Eigenfunctions of a partially filled rectangular waveguide. *Radiophysics and Quantum Electronics*, Vol. 33, Iss. 12, pp. 1023-1028. DOI: 10.1007/bf01040145

[15] Bovtun V., Kempa M., Kamba S., Pashkov V., Molchanov V., Poplavko Y. and Yakymenko Y. (2013) Microwave characterization of dielectric substrates for thin films deposition. *2013 IEEE XXXIII International Scientific Conference Electronics and Nanotechnology (ELNANO)*. DOI: 10.1109/elnano.2013.6552081

[16] Koledintseva M.Y., Drewniak J.L. and Hinaga S. (2011) Effect of anisotropy on extracted dielectric properties of PCB laminate dielectrics. *2011 IEEE International Symposium on Electromagnetic Compatibility*. DOI: 10.1109/isemc.2011.6038366

[17] Manoylov V. P. and Chuhov V. V. (2006) Calculation of the waveguied with the shape dielectric fulfills, *Visnyk NTUU KPI Seriia - Radiotekhnika Radioaparatobuduvannia*, Iss. 33, pp. 91-100. DOI: 10.20535/RADAP.2006.33.91-100

[18] Chukhov V. (2004) Method of dielectric permeability type determination and its measurement. *The Fifth International Kharkov Symposium on Physics and Engineering of Microwaves, Millimeter, and Submillimeter Waves (IEEE Cat. No.04EX828)*. DOI: 10.1109/msmw.2004.1346162

[19] Sidorchuk O.L., Manoilov V.P. (2013) Method of measurement of EPR. *Microwave & Telecommunication Technology (CriMiCo-2013)*, pp. 546–547

[20] Manoilov V. P. and Sydorchuk O. L. (2014) *Systema dlia nepriamoho vyznachennia antennoi skladovoi efektyvnoi poverkhni rozsiiuvannia aperturnykh anten* [The system for the indirect use of an antenna for warehouse warehousing of effective surface apertures]. Patent UA106557

Метод вимірювання ефективної діелектричної проникності частково заповнених хвилеводів за допомогою неузгодженого Т-мосту

Каращук Н. М., Манойлов В. П., Сидорчук О. Л., Тарасенко С. М., Чухов В. В.

Вступ. У техніці надвисоких частот широко застосовуються хвилеводи, що частково заповнені діелектричним матеріалом – частково-заповнені хвилеводи. Вони мають переваги порівняно із порожнистими хвилеводами, зокрема можливості щодо зменшення розмірів поперечного перетину, збільшення потужності випромінювання та подавлення небажаних типів хвиль. У зв'язку з випуском нових різноманітних діелектричних матеріалів, призначених для використання в пристроях діапазону надвисоких частот з малими втратами, має місце необхідність постійно розвивати методи розрахунку та методи вимірювання характеристик частково-заповнених хвилеводів.

Постановка проблеми. Теорія хвилеводів, заповнених повністю і хвилеводів з діелектричним заповненням вздовж вузьких стінок, розроблена достатньо повно. Проте її застосування до різних хвилеводних пристроїв потребує розв'язку трансцендентних рівнянь, що можливо лише чисельними методами. Це ускладнює отримання інформації про будь-яку характеристику пристрою. Також впливає велика кількість факторів, від яких залежать характеристики частково-заповнених хвилеводів (ступінь заповнення, положення пластини у хвилеводі, величина діелектричної проникності тощо). Розв'язок електродинамічної задачі для частково-заповнених хвилеводів зводиться до пошуку сталої поширення в хвилеводі. Точний розв'язок рівняння Гельмгольца електромагнітного поля для таких

хвилеводів можливий лише в окремих випадках, наприклад, в шаруватих хвилеводах, коли межа розподілу підкоряється кусково-неперервним законом розподілу проникностей. Класичні методи визначення сталих поширення в частково-заповнених хвилеводах зводяться до розв'язку дисперсійного рівняння, отриманого або методом прирівнювання тангенційних складових електричного та магнітного полів на межах розподілу кожного шару, або методом теорії кіл. Для дослідження частково-заповнених хвилеводів з різною висотою зразка, серед інших, пропонується підхід, який базується на поданні відносної діелектричної проникності середовища у вигляді двох дійсних функцій, кожна з яких залежить у поперечному перетині від однієї координати. Це наближена методика визначення власних скалярних і векторних функцій частково-заповнених хвилеводів. Отже, розв'язок електродинамічної задачі для частково-заповнених хвилеводів зводиться до пошуку сталої поширення в хвилеводі точними або наближеними методами. У статті розглядається метод, який дозволяє, вимірявши значення ефективної діелектричної проникності, розрахувати сталу поширення за будь-якої частоти.

Результати. За результатами проведеного аналізу показано, що відомі методи вимірювання ефективної діелектричної проникності (за допомогою вимірювальної лінії, панорамного вимірювача, мостового вимірювача) мають недоліки щодо залежності від модифікації частково-заповнених хвилеводів, вузькосмуговості, значної відносної похибки вимірювання за збільшення ефективної діелектричної проникності. Зокрема, недоліком мостових вимірювачів є дуже вузький частотний діапазон, в якому міст залишається узгодженим. Практично необхідно узгоджувати міст на кожній частоті, досягаючи відсутності сигналу в плечі Е за однакових навантажень, що підключені до бокових плечей. Для цього мости мають налаштувальні елементи у вигляді штирів, діафрагм та ін. Запропоновано метод вимірювання ефективної діелектричної проникності частково заповнених хвилеводів за допомогою неузгодженого Т-мосту, який вказаних недоліків не має.

Висновки. Наукова новизна запропонованого методу вимірювання ефективної діелектричної проникності частково-заповнених хвилеводів за допомогою неузгодженого Т-мосту полягає у можливості забезпечення широкосмуговості, підвищенні точності вимірювань, універсальності за рахунок застосування панорамного вимірювача коефіцієнта стоячої хвилі за напругою та електронно-обчислювальної машини. Особливістю також є можливість вимірювання ефективної діелектричної проникності у випадках такого частково-заповненого хвилеводу, де інші методи вимірювань не підходять. Отримані результати доцільно застосовувати під час проектування нових антенних систем, до складу яких входять частково-заповнені хвилеводи, а також у навчальному процесі для створення нових або удосконалення існуючих робочих місць для проведення лабораторних та практичних занять з використанням наведеного методу вимірювання.

Ключові слова: ефективна діелектрична проникність; часткове діелектричне заповнення; метод вимірювання ефективної діелектричної проникності; частково заповнений хвилевід

Метод измерения эффективной диэлектрической проницаемости частично заполненных волноводов с помощью несогласованного Т-моста

Каращук Н. Н., Манойлов В. Ф., Сидорчук О. Л., Тарасенко С. М., Чухов В. В.

В технике сверхвысоких частот широко используются волноводы, которые частично заполнены диэлектрическим материалом – частично-заполненные волноводы. Они имеют преимущества по сравнению с полыми волноводами, состоящие в возможности уменьшения размеров их поперечного сечения, увеличения мощности излучения и подавления нежелательных типов электромагнитных волн. В связи с выпуском новых разнообразных диэлектрических материалов, предназначенных для использования в устройствах диапазона сверхвысоких частот с малыми потерями, возрастает необходимость развивать методы расчета и методы измерения характеристик частично-заполненных волноводов. Решение электродинамической задачи для частично-заполненных волноводов сводится к поиску постоянной распространения электромагнитной волны в волноводе точными или приближенными методами. В статье рассмотрен метод, позволяющий измерить значение эффективной диэлектрической проницаемости и рассчитать постоянную распространения волны на любой частоте. Показано, что известные методы измерения (с помощью измерительной линии, панорамного измерителя, мостового измерителя) имеют недостатки в зависимости от модификации частично-заполненных волноводов, узкополосности, значительной относительной погрешности измерения. Предложенный метод измерения эффективной диэлектрической проницаемости частично-заполненных волноводов основан на применении несогласованного Т-моста, что обеспечивает высокую точность и широкополосность измерения. Для увеличения быстродействия измерения применена электронно-вычислительная машина. С ее помощью, благодаря различным программно-установленным компонентам, осуществляется статистическая обработка результатов, определяются характерные точки на графиках или рассчитываются другие производные параметры. Предложенный метод можно использовать для разработки и изготовления новых антенных систем, в состав которых входят частично-заполненые волноводы, а также в учебном процессе для подготовки специалистов соответствующей отрасли.

Ключевые слова: эффективная диэлектрическая проницаемость; частичное диэлектрическое заполнение; метод измерения эффективной диэлектрической проницаемости; частично заполненный волновод