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Electrodynamic analysis and design of bandpass filters on circular waveguides

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The possibility of using a circular waveguide with radial ridges and ring-shaped segments of finite thickness as resonant diaphragms in the synthesis of bandpass cylindrical waveguide filters is shown. The analysis of the electrodynamic parameters dependences on diaphragms geometrical dimensions has been carried out. Filters were synthesized and compared with experimental data.

Keywords: band pass filter, circular waveguide, resonant diaphragm with complex cross section.

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Introduction

Cylindrical waveguide structures with various heterogeneities of complex cross-section are widely used in ultra-high frequency (UHF) technology [1–4]. They have selective properties, which makes it possible to construct various waveguide UHF filters [5]. To reduce the weight and size of the filter, planar-transverse resonators in the form of thin metal diaphragms [6] are used instead of the classic volumetric resonators. At the same time, the main contribution to the size of the filter is made by the quarter-wave sections of the regular waveguide, which act as resistance inverters. Such filters are smaller, have better attenuation in the stop band and can use segments of circular waveguides with arbitrarily located ridges.

Various computer simulation packages are often used in the design of UHF devices. However, the success of this process and the time spent are highly dependent on the choice of the initial approximation. This is due to the need for multiparameter optimization of the electrodynamic characteristics of the simulated device. Thus, it turns out that the choice of the design of the filter prototype and its initial dimensions is relevant and affects the efficiency of the use of computer simulation packages and multiparameter optimization in the future, therefore, this paper considers an approach to the design of band-pass filters on round waveguides with diaphragms of a complex cross-section and obtaining the optimal design of the filter prototype for its further optimization. This paper shows that it is possible to use a circular waveguide with radial ridges and annular segments of finite thickness (Fig. 1) as resonant diaphragms [7] in the synthesis of band-transmitting waveguide filters based on cylindrical waveguide structures [8].

When designing the prototype filter and its further optimization, a previously tested approach to simulation of selective devices [9] was used. According to it, we set the parameters of the band-pass filter (for example, the fifth-order filter, the bandwidth $\Delta f = 400\,\text{MGz}$, the diameter of the round waveguide is 30 mm) and determine the Q-values of the resonant diaphragms [10]. Further, we need to determine the size of the resonant diaphragms that meet the given criteria. For this purpose, the problem of diffraction of the main wave on an infinitely thin diaphragm (Fig. 1) in a circular waveguide was solved. First of all, we are interested in the conductivity of heterogeneity and its S parameters. To find the reflection and transmission coefficients, we calculate the electric fields at the heterogeneity aperture $\mathbf{E}_N(r, \varphi)$. Then the reflectance Γ_1 and pass-through T_1 coefficients for the main wave can be found as:

$$1 + \Gamma_1 = \int_L \mathbf{E}_N(r, \varphi)\sigma_1 \mathbf{E}(r, \varphi)dL$$

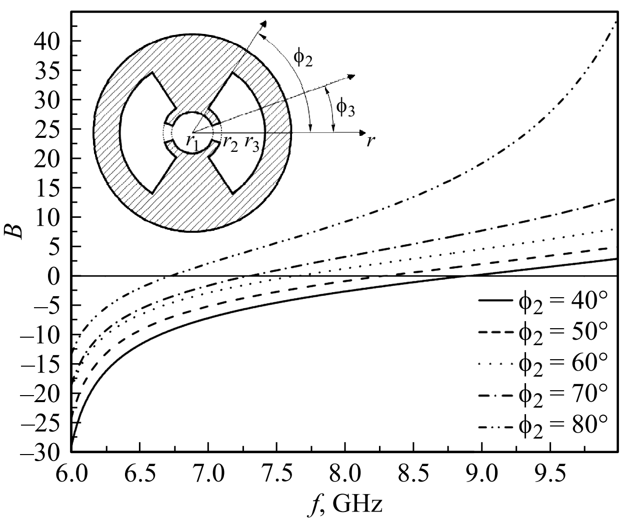

Figure 1. Diaphragm conductivity and diaphragm cross-section.

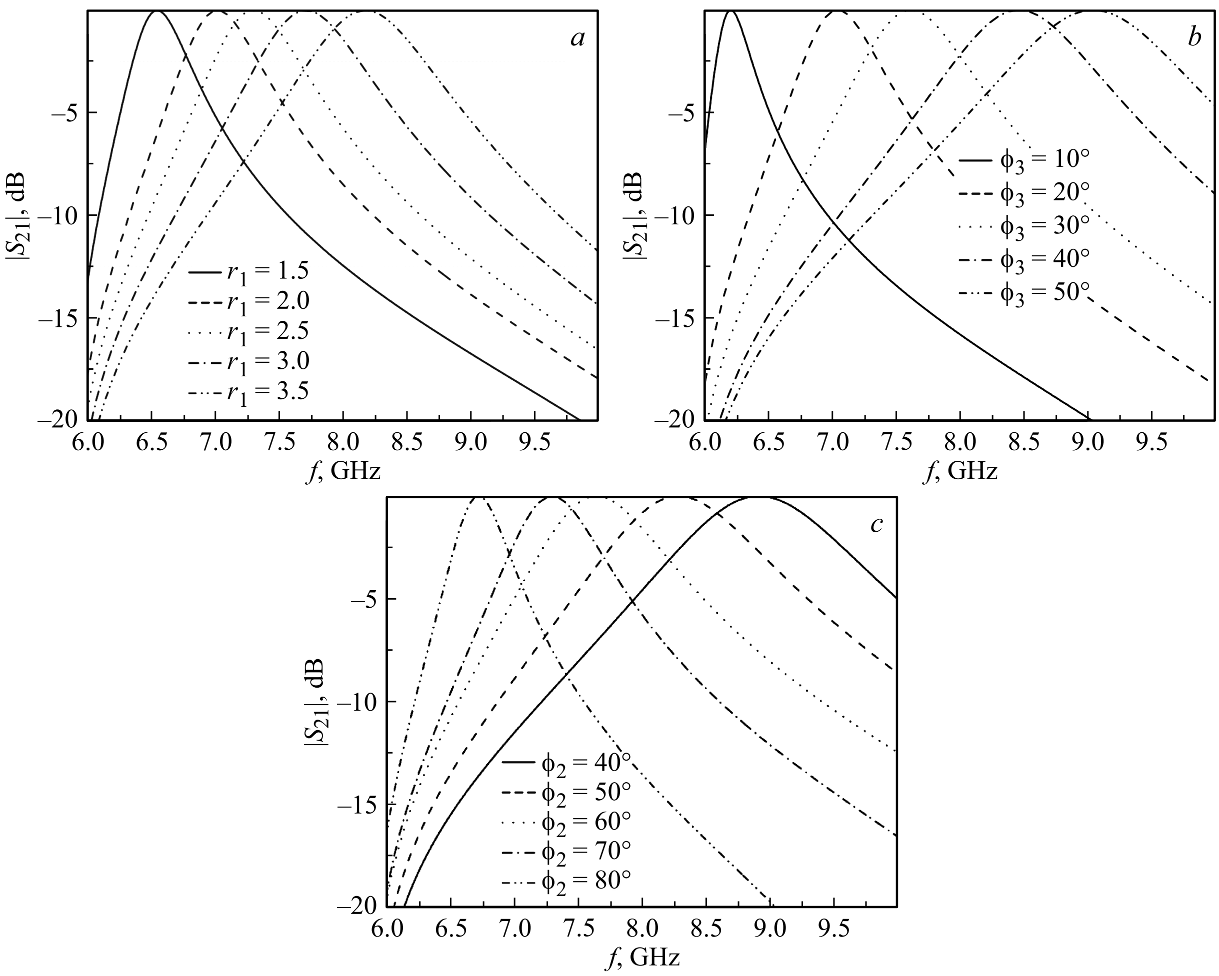

Figure 2. Transmission Ratio Module vs. Frequency and Aperture Size.

and

$$T_1 = \int_L \mathbf{E}_N(r,\varphi)\sigma_1\mathbf{E}(r,\varphi)dL,$$

where $\mathbf{E}(r,\varphi)$ — is the eigenfunction of the waveguide's main wave,

$$\sigma_1 = \left(\int_L \left(\mathbf{E}(r,\varphi)\right)^2 dL\right)^{-1}$$

— the weight factor, L — the heterogeneity aperture that considers its shape. Further, it is possible to define the electric field on heterogeneity as the sum of the eigenfunctions of its aperture with unknown numerical coefficients, which are determined from the solution of the system of linear algebraic equations according to the previously described method [9]. This makes it possible to determine the electric field for heterogeneity, the complex reflectance and propagation coefficients, and the conductivity of the diaphragm: $G + jB = (1 - \Gamma_1)/(1 + \Gamma_1)$. The developed method has allowed to calculate the parameters of interest to us. For example, Fig. 1 shows the dependence of the imaginary part of the shunt conductivity B normalized for the wave impedance of the excitation line for a single diaphragm on the dimensions of the heterogeneity sector at $\varphi_3 = 25°$, $r_1 = 2.5$ mm, $r_2 = 4.5$ mm, $r_3 = 6$ mm. It can be seen that increasing the angle of the radial ridge φ_2 significantly shifts the resonant frequency of the diaphragm. The calculations showed that the change in the outer radius of the ring segment r_2 practically does not change the resonant frequency of the diaphragm.

To analyze the resonance properties of a single diaphragm, elements of a scattering matrix were calculated. Fig. 2 shows the results of the calculation of the modulus of the coefficient of passage $|S_{21}|$ as a function of frequency when changing the different geometric dimensions of the heterogeneity. The rest of the structure parameters have the following dimensions: $r_2 = 4.5$ mm, $r_3 = 6$ mm, in Fig. 2, *a*: $\varphi_2 = 70°$, $\varphi_3 = 25°$, and $r_1 = 2.5$ mm, $\varphi_2 = 70°$ (Fig. 2, *b*) and $\varphi_3 = 25°$ (Fig. 2, *c*). As can be seen from the figures, a change in the geometric dimensions of a radial edge leads to a significant change in the modulus of the passing coefficient.

The calculations showed that the angle of the radial ridge φ_2, the angle of the annular segment φ_3 and the radius of the annular segment r_1 have the greatest influence on the resonant frequency and the diaphragm's loaded Q-factor determined by the width of the resonant curve. It should be noted that the outer radius r_3 of a single aperture has little to no effect on its Q-factor. However, it significantly shifts the resonant frequency. The calculations and analysis of the results made it possible to identify the geometric dimensions of the heterogeneity, which significantly affect only the displacement of the resonant frequency, as well as the parameters that affect both the resonant frequency and the Q-factor of the diaphragm itself. Such different behavior of the resonance characteristics of heterogeneity from its geometric dimensions makes it possible to make a more accurate selection of the parameters of frequency-selective devices that meet the specified requirements. Owing to a large number of variable parameters, it is possible to calculate the geometric dimensions of resonant diaphragms with the required Q-factor and while maintaining the same resonant frequency.

Thus, the design of the filter can be carried out in two stages.

1. Electrodynamic calculation of a resonant diaphragm, which includes: selection of the type of heterogeneity and geometry of its aperture; Solution of the boundary value problem for an equivalent waveguide with a complex cross-section and determination of its eigenvalues and eigenfunctions and solution of the diffraction problem in the single-mode mode of operation (for this purpose, we can equate the fields of the main wave of the waveguide and the field on the aperture, which in turn is given by the expansion according to its proper functions). The result: calculation of the reflection and propagation coefficients for the main wave, as well as the complex conductivity of the diaphragm.

2. Filter synthesis: set the required filter characteristics (bandwidth, stop band, attenuation levels), determine the required number of links, calculate the filter coefficients with quarter-wave couplings that implement the Chebyshev characteristic, determine the Q-factor of the filter resonators. Further, to calculate the geometry of the apertures of the resonant diaphragms that realize the required Q-factor, calculate the lengths of the quarter-wave segments of the waveguide, build a three-dimensional model of the prototype filter with the obtained geometric dimensions and, knowing the influence of various parameters on the resonance characteristics of heterogeneity, optimize the geometric parameters of the filter, for example, in the CST STUDIO SUITE package.

The approach used and the calculations made it possible to simulate a prototype of the filter, in which the studied diaphragms in the form of a radial ridge and a ring segment of finite thickness were used as resonators, and regular quarter-wave segments of a round waveguide were resistance inverters. The obtained geometric dimensions of the resonant diaphragms were used as an initial approximation for the synthesis of band-pass filters in the CST STUDIO SUITE software package. At the same time, it should be noted that the detailed dependencies of the conductivity

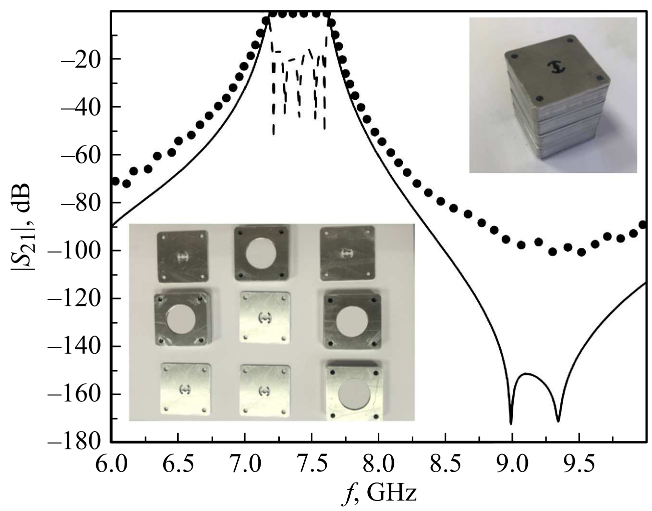

Figure 3. Amplitude-frequency response of the synthesized filter, experimental data (markers) and photos of the created filter assembly and component.

and the modulus of the passing coefficient on the geometric parameters allow you to optimally set the optimization parameters, which significantly reduces the time spent on this time-consuming process. As a result, a third-order filter was designed with a bandwidth of 400 MGz (7.22–7.62 GHz), a bandwidth transmission coefficient unevenness of up to −0.7 dB and a reflectance of 33 dB. At the same time, its longitudinal size was 26.34 mm, and the longitudinal size of the fifth-order filter was only 43.66 mm. At the same time, the bandwidth of the fifth-order filter was in the range of 7.17–7.63 GHz, and the reflection coefficient was not worse than 16.35 dB (Fig. 3).

To carry out experimental verification of the results of numerical simulation, appropriate filters were manufactured. For example, Fig. 3 shows photos of a fifth-order filter and shows the results of a comparison of the calculated characteristics in computer simulation (solid line $|S_{21}|$, dotted line $|S_{11}|$) with the measured parameters (markers $|S_{21}|$) of the manufactured prototype filters for the fifth-order filter. There is a good coincidence of the compared values, which indicates the high accuracy and reliability of the proposed methods for designing UHF filters.

Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] S. Ekici, E. Yazgan. Microwave Opt. Technol. Lett., **64**, 1707 (2022). DOI: 10.1002/mop.33356

[2] D.V. Lonkina, D.S. Gubsky, V.V. Zemlyakov. Radiotekhnika i elektronika, **65** (9), 835 (2020) (in Russian). DOI: 10.31857/S0033849420090053

[3] S. Ekici, E. Yazgan. Electromagnetics, **41** (1), 1 (2021). DOI: 10.1080/02726343.2021.1864577

[4] J. Li, L. Guo, S. Xie. *IEEE MTT-S Intern. Wireless Sympos.* (IWS) (Harbin, China, 2022), p. 1. DOI: 10.1109/IWS55252.2022.9977509
[5] S.Y. Yu, J. Bornemann. *bProceedings of 2011 IEEE Pacific Rim Conference on Communications, Computers and Signal Processing* (Victoria, BC, Canada, 2011), p. 504–508. DOI: 10.1109/PACRIM.2011.6032945
[6] D.S. Gubsky, V.V. Zemlyakov, D.V. Lonkina. Radiotekhnika i elektronika, **64** (1), 22 (2019) (in Russian). DOI: 10.1134/S0033849419010078
[7] D.V. Lonkina, V.V. Zemlyakov, D.S. Gubsky, G.F. Zargano, S.V. Krutiev. Izvestiya Vuzov. Radiofizika, **64** (5), 395 (2021). (in Russian). DOI: 10.52452/00213462_2021_64_05_395
[8] E. Musonda, I.C. Hunter. IEEE Transactions on Microwave Theory and Techniques, **63** (3), 954 (2015). DOI: 10.1109/TMTT.2015.2389216
[9] V. Zemlyakov, M. Tyaglov, V. Shevchenko. J. Electromagnetic Waves and Applications, **34** (2), 224 (2020). DOI: 10.1080/09205071.2019.1697379
[10] A.L. Feldshtein, L.R. Yavich, V.P. Smirnov. *Waveguide Elements Handbook* (Sov. Radio, M., 1967), 651 p.

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