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ARTICLE *in* JOURNAL OF COMMUNICATIONS TECHNOLOGY AND ELECTRONICS · JANUARY 2014

Impact Factor: 0.39 · DOI: 10.1134/S1064226914010033

2 AUTHORS:

Natalia A. Bogatykh

Kotel'nikov Institute of Radioengineering an…

V. A. Kaloshin

Kotel'nikov Institute of Radioengineering an…

ISSN 1064-2269, Journal of Communications Technology and Electronics, 2014, Vol. 59, No. 1, pp. 54–60. © Pleiades Publishing, Inc., 2014.
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ANTENNA AND FEEDER SYSTEMS

On Matching of Symmetric TEM Horns

N. A. Efimova[a, b] and V. A. Kaloshin[b]

[a] *Moscow Technical University of Communications and Informatics, Aviamotornaya ul. 8a, Moscow, 111024 Russia*

[b] *Kotel'nikov Institute of Radio Engineering and Electronics, Russian Academy of Sciences, Mokhovaya ul. 11, str. 7, Moscow, 125009 Russia*

e-mail: e.natalie86@gmail.com, vak@cplire.ru

Received July 5, 2013

Abstract—Using an asymptotic solution to the 2D diffraction problem for the open end of a horn, the method transverse sections, and the results of the numerical analysis, a numerical–analytical model for matching of symmetric TEM horns is built. The finite element method is used to estimate the accuracy of this model. The model is used to find optimum values of the input and output characteristic impedances as well as the variation law of this impedance along the horn length optimal from the viewpoint of obtaining the minimum value of the low-frequency boundary of matching at a level of −10 dB for a semiinfinite frequency band. The finite element method is used to refine the values of the determined parameters. Matching characteristics of synthesized horns are compared with available results.

DOI: 10.1134/S1064226914010033

INTRODUCTION

Regular and irregular symmetric TEM horns are the radiators that are widely used as ultra-wideband (UWB) antennas [1–12]. The geometry of a hollow regular horn is described by three parameters, horn length a and flare angles α and β (Fig. 1), which determine matching. In the case of an irregular horn, angles α and β are functions of x (Fig. 2). Synthesis of a horn optimal from the viewpoint of matching, i.e., having minimum overall dimensions in a prescribed frequency band, is reduced to determination of functions $\alpha(x)$ and $\beta(x)$.

Works devoted to the study of various designs of irregular TEM horns were analyzed in report [2] and two methods for determination of functions $\alpha(x)$ and $\beta(x)$ optimal from the viewpoint of matching were selected.

The first method is based on the numerical solution of the direct problem of calculation of the reflection coefficient of the TEM horn. In this method, the horn generatrix is represented as a function specified by a finite number of parameters whose values are then optimized [3, 4]. An advantage of this method is that it is well suited for application of standard computer simulation and optimization algorithms with obtaining the result optimal in the framework of the applied algorithm. Disadvantages of this method are large required computer time without confidence in reaching the global optimum.

In the other method, an analytical model of the TEM horn is built and optimization is performed within framework of this model. In this method, the TEM horn is considered as an irregular waveguide transition from the excitation unit to free space [5–10]. In order to find functions $\alpha(x)$ and $\beta(x)$, a function describing variations in the characteristic impedance of the transmission line from the excitation unit to the horn aperture is selected. Most often, the exponential law is used to describe variation in the characteristic impedance along the horn length from input characteristic impedance Z_{in} (the impedance at the junction with the excitation unit) to output characteristic impedance Z_{out}. The input impedance is usually selected equal to the characteristic impedance of the feeding line (50 Ω) and the output impedance, to the characteristic impedance of free space (120π Ω). Then, the characteristic impedance in each horn section is related to the horn geometrical parameters. For this purpose, the well-known microstrip approximation is usually applied (see, e.g., [5–7, 9, 10]. An advantage of this method is the possibility of analytical formulation of the optimization problem. Among disadvantages are inaccurate description of the frequency dependence of the reflection coefficient and relation between geometrical parameters of the horn and the characteristic impedance. Moreover, the method is limited to the type of the function chosen for description of the characteristic impedance and can be used for the search for functions $\alpha(x)$ and $\beta(x)$ only within the limits of the approximation used to relate the characteristic impedance and the geometrical parameters of the horn. In this method, the horn matching characteristics are determined by its input and output impedances and the law of variation of the characteristic impedance along the horn length $Z(x)$.

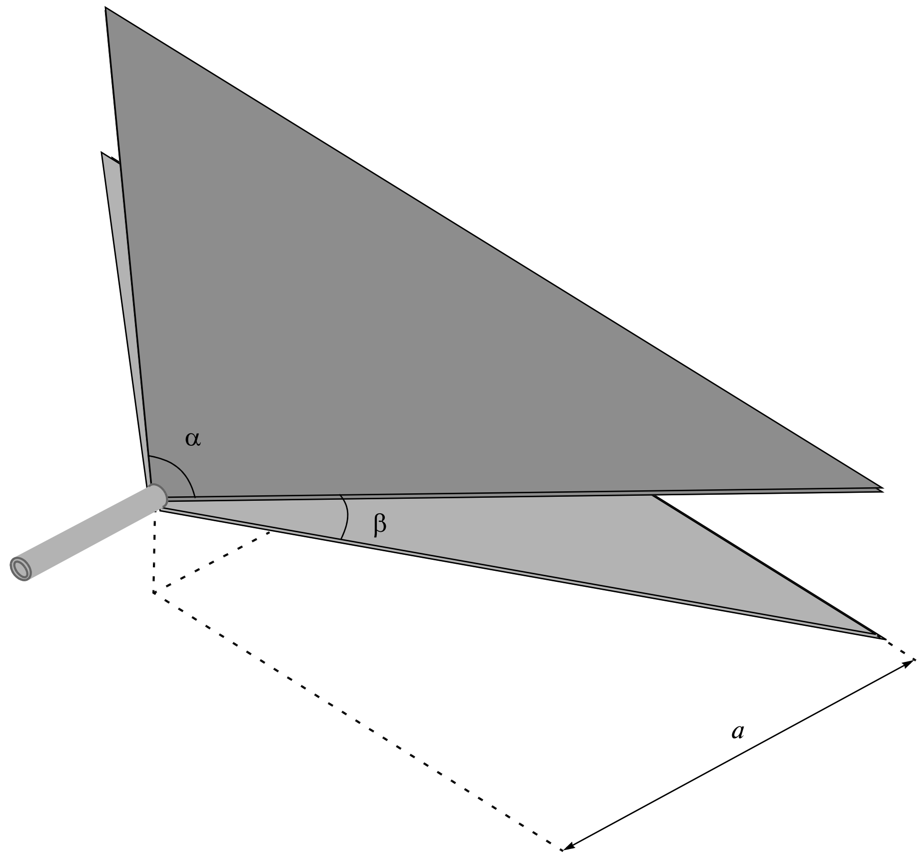

Fig. 1. Layout of a TEM horn.

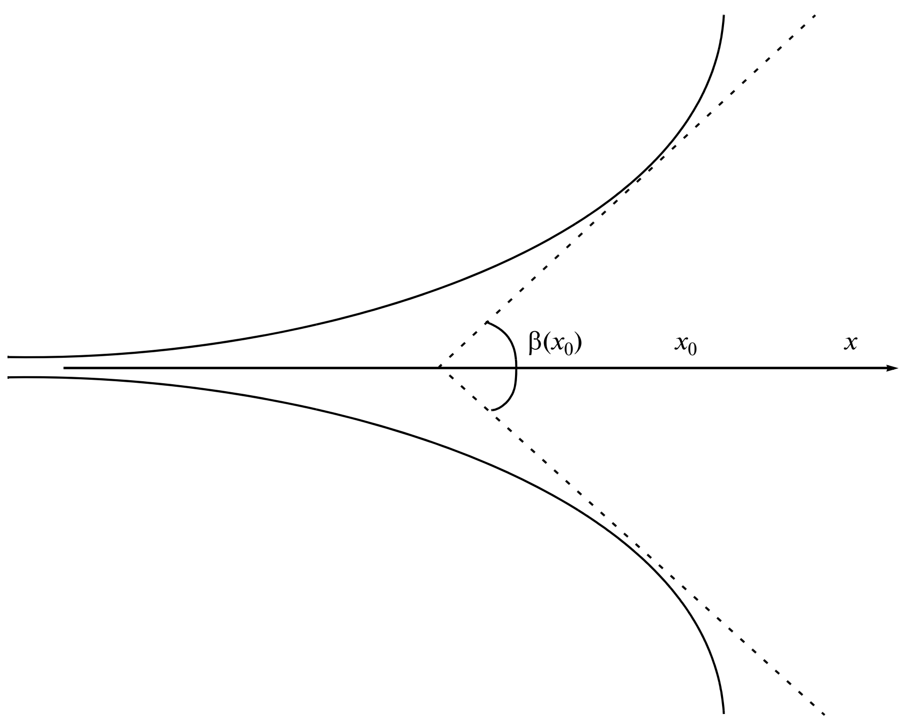

Fig. 2. *E*-plane section of an irregular horn.

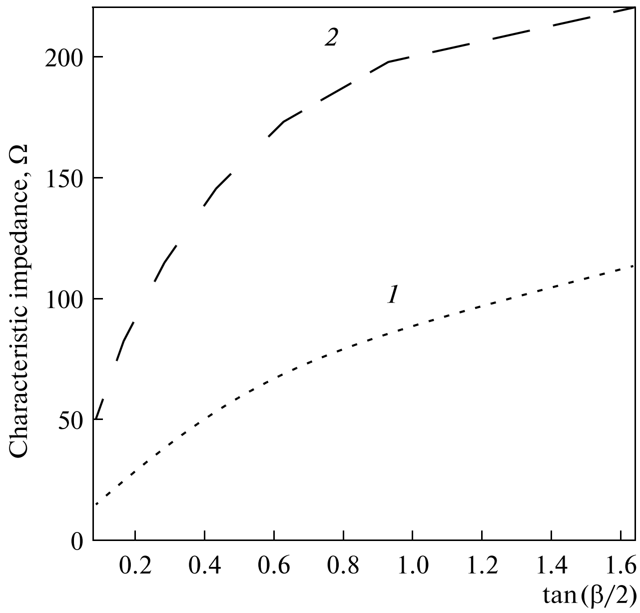

Fig. 3. Characteristic impedance of the regular horn as a function of tan(β/2): (*1*) microstrip approximation and (*2*) calculation for the TEM horn.

In this study, we restrict our analysis to the case $\alpha =$ const, i.e., we optimize function $\beta(x)$, which is related to the characteristic impedance of the irregular TEM horn on the basis of the results of numerical calculations obtained in [14] for a regular horn. Asymptotic formulas derived in [15] are used to take into account reflection from the open end of the horn. The constructed numerical–analytical model of a symmetric irregular horn is used to minimize the lower matching frequency at a level of –10 dB for a semiinfinite frequency band. The accuracy of this model is tested by comparing the frequency dependence of the reflection coefficient obtained with this model and a similar dependence calculated using the finite element method (FEM). Refinement of the optimization results is also performed with the use of the FEM model.

1. NUMERICAL–ANALYTICAL MODEL

As was mentioned above, usually, the microstrip approximation is selected to describe the relation between the geometric parameters of the horn and the characteristic impedance. In order to test the accuracy of this approximation, the characteristic impedance of a regular TEM horn was calculated as a function of $\tan(\beta/2)$ with the use of the well-known formulas for the microstrip line (see, e.g., [13]) and the numerical data on the characteristic impedance of a TEM horn [14]. The results are compared in Fig. 3. As seen from this figure, the microstrip approximation rather coarsely describes the characteristic impedance of a regular horn. Hence, we decided to abandon this approximation and use the numerical solution for the TEM horn [14]. Here, in accordance with the ideas of the method of transverse sections, we assume that the characteristic impedance of an irregular horn coincides with the characteristic impedance of a regular horn (shown by the dashed lines in Fig. 2) tangential in this section to the irregular horn. Data on the characteristic impedance are given in [14] as a set of level lines. In this study, the data describing function $Z(\beta)$ at $\alpha =$ const were interpolated by a polynomial in variable β.

In the numerical–analytical model of an irregular TEM horn, reflection coefficient R is represented as a sum of three components. The first component describes contribution to the reflection coefficient from the excitation unit; the second part, contribution from the irregular part of the horn; and the third part, contribution from the horn aperture.

Expressions for the first and second components of the reflection coefficient can be readily obtained from the theory of long transmission lines, according to which the contribution from the input can be represented as

$$R_1 = \frac{Z_0 - Z_{\text{in}}}{Z_0 + Z_{\text{in}}}, \qquad (1)$$

where Z_0 is the impedance of the feeding line, and the contribution from the irregular part of the horn has the form (see, e.g., [16])

$$R_2 = \int_0^a \frac{Z'}{2Z} \exp(2Ikx)dx, \qquad (2)$$

where $Z(x)$ id the law describing variation in the horn characteristic impedance along the horn length, $x \in [0, a]$, and k is the wave number of free space.

The third component is found by means of asymptotic expansion of the reflection coefficient for the horn end, which was obtained in [15]. The expression for the first term of the reflection coefficient can be written as follows:

$$R_3 = \frac{\sqrt{2\pi}}{2ka\beta} \exp\left(I\frac{\pi}{2} + 2Ika\right) g(0,0,c), \qquad (3)$$

where $g(\alpha,\beta,c) = g^- + \varepsilon g^+$ and $g^{\pm}(\alpha,\beta,c) = \frac{1}{c}\sin\frac{\pi}{c}\left(\cos\frac{\pi}{c} - \cos\frac{\alpha \pm \beta}{c}\right)^{-1}$ is the diffraction coefficient describing the solution to the wedge diffraction problem. Here, c depends on the geometry of the horn aperture. In our case, in accordance with recommendations of paper [4], $c = 1.5$.

2. TESTING OF THE MODEL ACCURACY

Before passing to optimization, we estimate the accuracy of the numerical–analytical model for irreg-

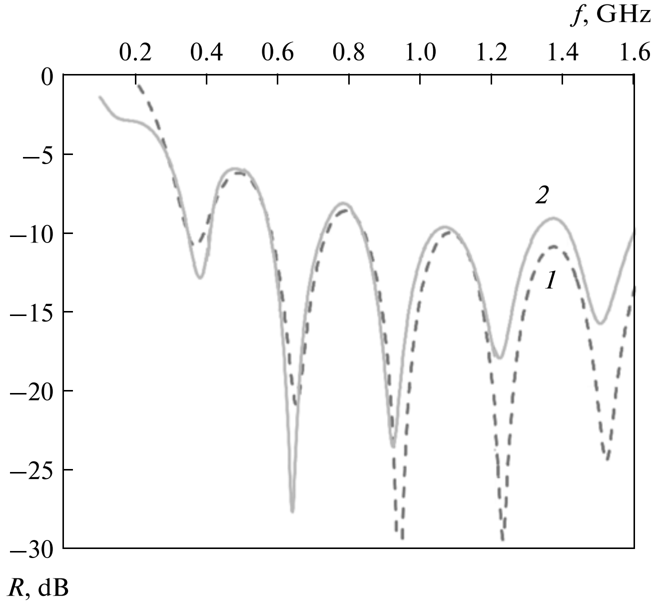

Fig. 4. Reflection coefficient of the horn with hyperbolic law of variation of the characteristic impedance having $Z''(x) > 0$ for $Z_{\text{in}} = 70\ \Omega$ and $Z_{\text{out}} = 100\ \Omega$.

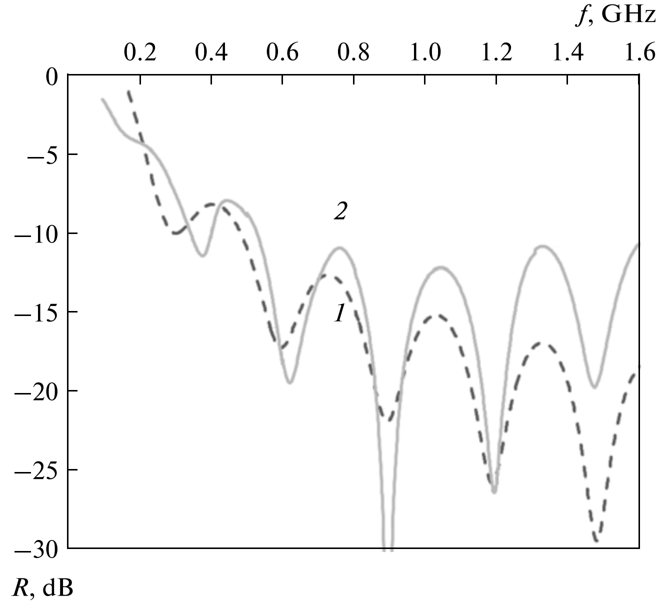

Fig. 5. Reflection coefficient of the horn with parabolic law of variation of the characteristic impedance having $Z''(x) < 0$ for $Z_{\text{in}} = 55\ \Omega$ and $Z_{\text{out}} = 100\ \Omega$.

ular horns with different input and output impedances and laws of variation of the characteristic impedance.

Frequency dependences of the reflection coefficient are presented in Figs. 4–6. Curves *1* were obtained with the use of the numerical–analytical model and curves *2*, with the use of the FEM model. The results obtained for a horn with hyperbolic law of variation of the characteristic impedance having positive second derivative ($Z''(x) > 0$) are shown in Fig. 4. The results obtained for a horn with parabolic law of variation of the characteristic impedance having negative second derivative ($Z''(x) < 0$) are shown in Fig. 5. The results obtained for horns with linear laws of variation of the characteristic impedance and different output impedances (100 and 195 Ω) are shown in Figs. 6a and 6b.

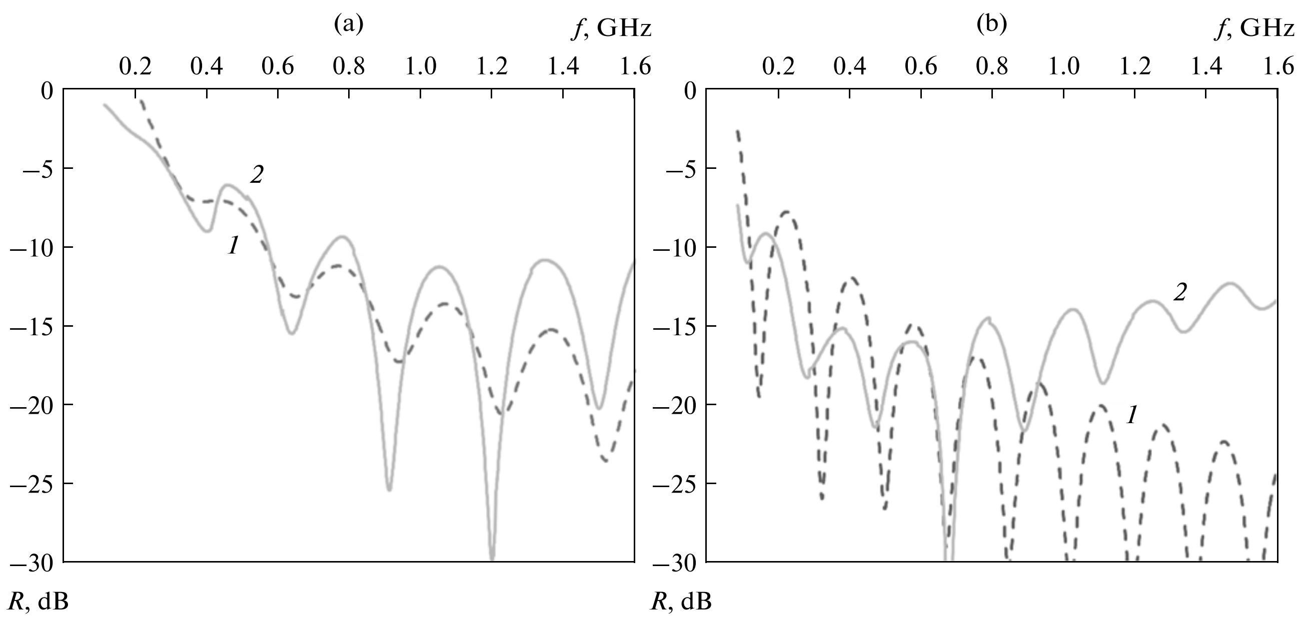

Fig. 6. Reflection coefficients of the horns with linear laws of variation of the characteristic impedance for $Z_{\text{in}} = 50\ \Omega$ and $Z_{\text{out}} =$ (a) 100 and (b) 195 Ω.

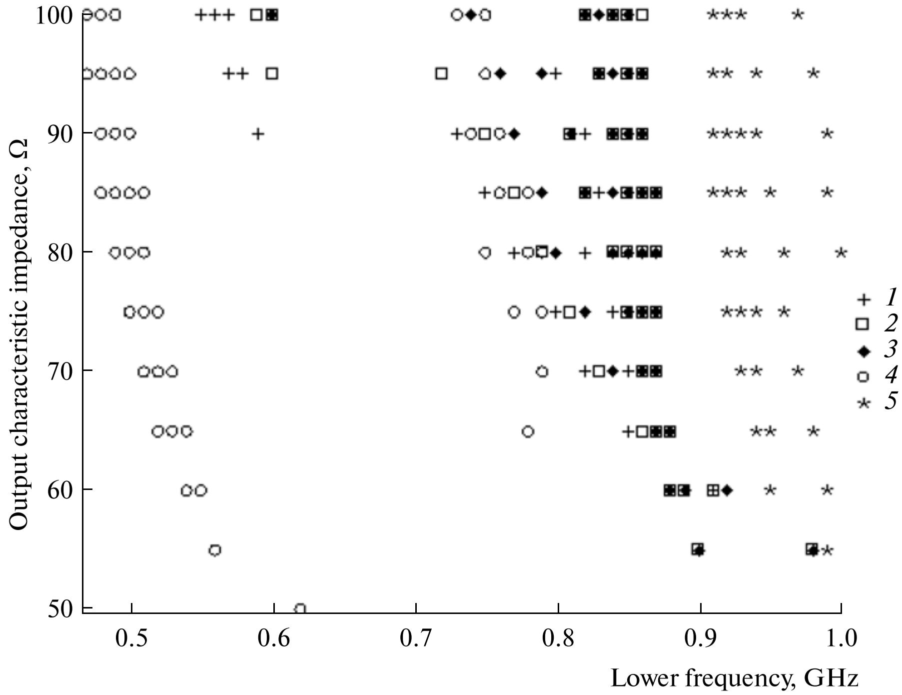

Fig. 7. Lower matching boundary at a level of –10 dB for horns with different laws of variation of the characteristic impedance: (*1*) corresponds to a linear law of variation of the characteristic impedance, (*2*) corresponds to an exponential law with $Z''(x) > 0$, (*3*) corresponds to a hyperbolic law with $Z''(x) > 0$, (*4*) corresponds to a parabolic law with $Z''(x) > 0$, and (*5*) corresponds to a parabolic law with $Z''(x) < 0$.

As seen from Figs. 4–6, the numerical–analytical model provides rather good description of the reflection coefficient of the TEM horn for different laws of variation of the characteristic impedance in the low-frequency region, especially in the case of small differences between Z_{in} and Z_{out}. At a matching level of –10 dB, the accuracy of this model remains satisfactory, which allows us to use it for optimization of function $\beta(x)$ in order to obtain horn matching at this level.

3. OPTIMIZATION OF MATCHING OF AN IRREGULAR TEM HORN

In order to optimize an irregular TEM horn, we calculated frequency dependences of the reflection coefficients of TEM horns with different input and output characteristic impedances and different laws of variation of this parameter along the horn length. Input and output characteristic impedances of these horns varied from 50 Ω to 100 Ω in steps of 5 Ω. As the laws of variation of the characteristic impedance, we have chosen a linear law, a hyperbolic law with $Z''(x) > 0$, and two types of a parabolic law: a law with $Z''(x) > 0$ and a law with $Z''(x) < 0$.

Table 1. Electric dimensions (*ka*) corresponding to the lowest matching frequency at a level of –10 dB for horns with a linear law of variation of the characteristic impedance

Z_{in}	Z_{out}				
	60	70	100	180	200
50	–	–	–	1.83	1.01
55	7.5	7.5	4.5	1.85	–
60	–	7.6	–	1.90	–
65	–	–	–	1.93	–

The results of calculations are shown in Fig. 7. Dots *1*–*4* correspond to the model of an irregular horn with a particular set of parameters. The lower matching boundary at a level of –10 dB is the dot coordinate along the abscissa axis and the output characteristic impedance of the horn (measured in ohms) is the coordinate of this dot along the ordinate axis. Different types of dots correspond to different laws of variation of the characteristic impedance. The difference in the input impedances (Z_{in}) of horns with identical laws of variation of the characteristic impedance is not shown.

As follows from the results presented in Fig. 7, the minimum value of the lower matching boundary can be obtained with irregular horns having either a parabolic law of variation of the characteristic impedance with $Z''(x) < 0$ or a linear law of variation. It can also be seen that, among the horns with the same law of variation of the characteristic impedance, horns with larger values of the output impedance have the lowest values of the low-frequency matching boundary.

Table 2. Dimension efficiencies of different models of TEM horns

References	DE	Model description
This paper	0.56	Irregular horn with linear law of variation of the characteristic impedance having $Z_{in} = 50\ \Omega$ and $Z_{out} = 200\ \Omega$
[3]	0.31	Wall generatrix is an optimized superellipse
[4]	0.48	Wall generatrix is an optimized exponent
[5]	0.34	Exponential law of variation of the characteristic impedance with $Z_{in} = 50\ \Omega$ and $Z_{out} = 120\pi\ \Omega$; geometrical dimensions are found with the help of the microstrip approximation
[6]	0.14	The design is similar to [5]; worse matching is the result of modification of the horn aperture
[7]	0.49	*E*-sectoral horn; remaining parameters are taken from [5]
[8]	0.29	The design is similar to [5]. The difference consists in application of numerical simulation for determination of geometrical parameters of each section
[9]	0.14	The design is similar to [5]. The difference consists in variation in the width of the horn wall at a constant value of angle *b*
[10]	0.53	*E*-sectoral horn; remaining parameters are taken from [5] with application of ideas from [11]
[11]	0.51	Combined symmetric horn, i.e., the horn considered as a combination of electric and magnetic radiators
[12]	0.25	Asymmetric horn with the wall geometry obtained by combining the method of equivalent circuits and the genetic optimization algorithm

The electric radii (ka) of the spheres circumscribing the horn at the lowest matching frequency at a level of −10 dB are listed in Table 1 for an irregular horn with a linear law of variation of the characteristic impedance and different values of the input and output impedances.

It can be seen that, among irregular horns with the same law of variation of the characteristic impedance and the same output impedance, horns with the input impedance equal the impedance of the feeding line (50 Ω) have the smallest electric dimension.

4. VERIFICATION OF THE RESULTS OF OPTIMIZATION

These conclusions were verified with the use of the FEM model. Tests have shown that the TEM horn with linear law of variation of the characteristic impedance, the maximum (for this model) output impedance ($Z_{out} = 200\ \Omega$), and the input impedance equal the impedance of a coaxial line ($Z_{in} = 50\ \Omega$) is the optimum horn from the viewpoint of matching.

To compare the results obtained in this study with the well-known results obtained with use of the FEM model, we calculated the dimension efficiency (DE) of the horn, a coefficient introduced in [4] (see Table 2).

As seen from Table 2, the DE of the irregular TEM horn optimized with the use of the numerical-analytical model proposed in this paper exceeds the DE of available symmetric TEM horns. This conclusion was then verified by means of numerical simulation with the use of the FEM model. The DE of the optimized TEM horn is less than the DE of the asymmetric loop TEM horn proposed in [4]; however, unlike the loop horn, the design analyzed in this paper does not require application of a ground.

CONCLUSIONS

In this study, we restricted our analysis to variation in only one angle (β) of two angles determining the horn geometry. Moreover, according to [14], the maximum allowable value of the output impedance corresponding to the selected α could not exceed 200 Ω, which also limited the capabilities of the optimization procedure. Probably, if the model would include variations in angle α and a larger limiting value of the of the output impedance, the DE of irregular TEM horns could be increased.

ACKNOWLEDGMENTS

This study was supported by the Russian Foundation for Basic Research, project no. 12-07-00717-a.

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Translated by A. Kondrat'ev