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Mathematical Model of a Square Waveguide Polarizer with Diaphragms

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***Abstract* — The development of new mathematical model for guide polarization converter with diaphragms was carried out in the research by the method of wave matrices. In addition, numerical modeling of the performance of a polarizer with diaphragms is made by simulating the propagation of the fundamental modes with perpendicular linear polarizations. The wave matrix model was obtained by splitting the polarizer into separate structural elements. Each element was described by its own wave transmission matrices. As a result, a general wave scattering matrix was formed. Based on the elements this matrix the electromagnetic characteristics of the considered polarizer were obtained theoretically. In particular, complex reflection and transmission coefficients were calculated. Their modules and phases were analyzed in the frequency interval 10.7–12.8 GHz. To check the correctness of the obtained results an independent numerical simulation was carried out applying the finite element methodology in the frequency interval. The results of both approaches are in good agreement. The engineered converter of polarization with four diaphragms provides a reflection coefficient modulus of less than 0.14 and a transfer coefficient modulus of more than 0.99 for two orthogonal types of polarizations. As a result, a rigorous mathematical method was developed to analyze the elements of the scattering matrix of a waveguide polarizer with diaphragms. It can be used for the development of new broadband waveguide polarizers and waveguide filters based on diaphragm elements.**

***Index Terms*—** Electromagnetic simulation, microwave passive devices, waveguide components, polarization, waveguide polarizer, diaphragm polarizer, wave matrix, reflection coefficient, transmission coefficient.

I. INTRODUCTION

The fast evolution of modern communication systems in the millimeter range has contributed to the emergence and development of adaptive antenna systems with double polarization signal processing [1], [2]. The key elements of such systems are polarization transforming passive devices including orthomode converters, guide polarizers and microwave duplexers.

The polarizer of an antenna system converts linearly polarized input electromagnetic waves into circularly polarized and performs the reverse transformation. Application of this waveguide component allows to enhance the information volumes and channel's capacity in wireless telecommunication systems. Polarization processing devices have various designs based on the

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circular or rectangular/square waveguides. The idea of constructing of polarizers is based on the introduction of a quasi-periodic or inhomogeneous structure into the waveguide that will implement a phase shift of 90º between the modes with two perpendicular polarizations [3]-[8].

Historically, the first microwave devices for transformation of electromagnetic waves' polarization type were based on waveguides with reactive pins [9]-[13]. Guide structures with posts provide developers with the possibility of adjustment of charactristics. On the other hand, the main disadvantage of the polarizer designs with pins is their relatively narrow operating frequency band. Operating range of waveguide devices can be extended using ridged structures and diaphragms. Recently, new kinds of polarizers, which are based on coaxial and other waveguides with mentioned discontinuities, began to appear [14]-[20]. They provide broad frequency bands, but contain a significant number of reactive elements in the form of diaphragms. This leads to the larger overall sizes of their designs, which is their main disadvantage. Besides, several novel designs of polarizers based on structures with sectoral coaxial ridged waveguides are reported in [21]-[27]. The application of coaxial guides allows to obtain dual-band operation of antenna systems based on them.

All existent types of waveguide polarizers require the utilization of complex mathematical methods for their analysis. Among them we can highlight field-matching technique [28]-[31] and integral equations technique [32]-[34]. Consequently, creation of new easier approaches for the analysis of characteristics of waveguide polarizers is a state-of-the-art scientific and engineering problem.

In dual-band polarization processing units the polarizers are used in conjunction with orthomode transducers. An orthogonal modes converter is a guide device that discriminates two orthogonal signals with linear polarization within their common frequency range [35]-[39]. In addition, the application of waveguide filters [40]-[46] in conjunction with polarizers improves the efficiency of polarization processing of signals in antenna systems.

Diaphragm polarizers are broadly utilized in state-of-the-art satellite telecommunication systems [47]-[52]. Besides, there are effective guide polarizer designs with diaphragms and pins [53]-[58]. The main advantage of a polarizer with diaphragms over guide polarizers of other types is the ability to provide the most broadband functioning with efficient parameters, which can be upgraded by adding additional diaphragms to the design. The disadvantage is the increase in the length of the polarizer, which occurs in this case.

Diaphragm polarizers can be realized in the form of separate plates, which are placed at a certain distance from each other. They can also be realized with one specially shaped plate. Such devices are called septum polarizers [59]-[66]. The septum divides the waveguide into two rectangular waveguides. These waveguides form ports that are used to transmit or receive linearly polarized or circularly polarized waves. Such polarizers are broadly applied in state-of-the-art 5G telecommunication systems of the millimeter wavelength range [67]-[75]. The disadvantage of such guide polarizers is complex mathematical methods of their analysis.

Therefore, the development of new mathematical model of a waveguide polarizer with diaphragms, which will allow to carry out fast analysis and optimization of its characteristics, including magnitudes and phases of the transmission and reflection coefficients, is a relevant scientific problem.

II. THEORETICAL ANALYSIS OF WAVEGUIDE POLARIZER WITH FOUR DIAPHRAGMS

The inner structure and overall dimensions of an investigated polarizer based on a waveguide with diaphragms are demonstrated in Fig. 1.

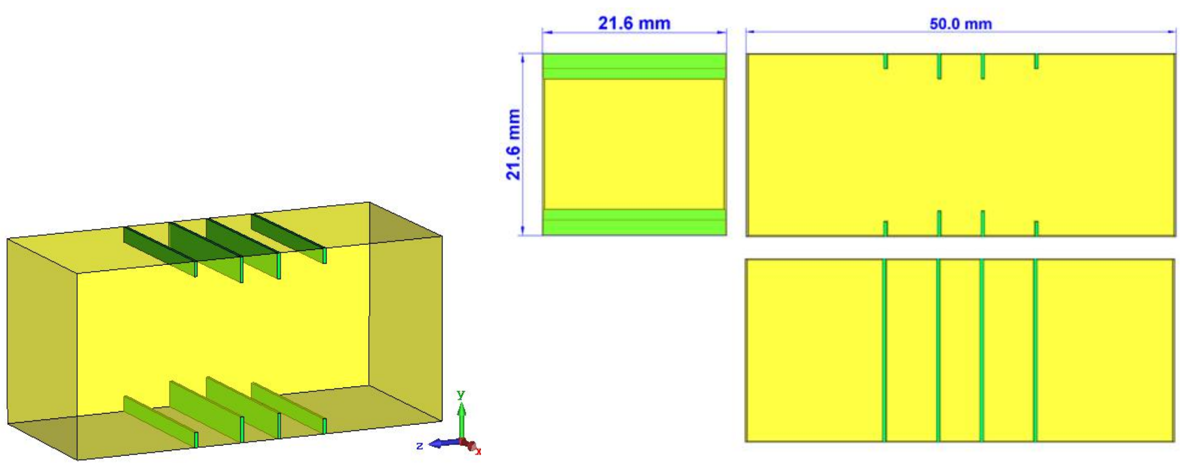

Fig. 1. The general view of a waveguide polarizer with four diaphragms.

The design of shown square guide polarizer contains four conducting diaphragms. The outer diaphragms are located symmetrically with respect to the inner diaphragms, which are located in the center of the waveguide.

For the theoretical analysis of the device we will use a single-wave approximation and the techniques of wave matrix theory [76]-[80]. The equivalent circuits of a waveguide polarizer for the case of inductive and capacitive diaphragms are given in Fig. 2.

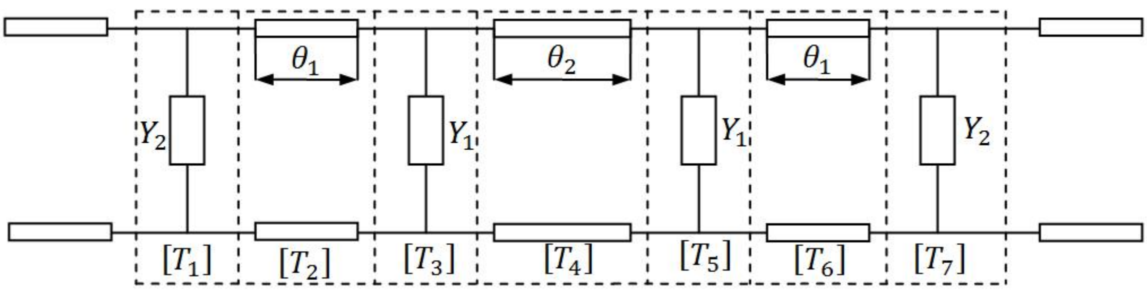

Fig. 2. Equivalent network of a waveguide polarizer with four diaphragms.

The conductivity of inductance diaphragm in the square waveguide is determined by the formula [81]

$$\mathrm{Y_L} \cong -j\frac{\lambda_w}{a}\cdot\left[ctg\left(\frac{\pi d}{2a}\right)\right]^2 \tag{1}$$

The conductivity of capacity diaphragm in the square waveguide is determined by the formula [81]

$$Y_C \cong j\frac{4a}{\lambda_w}\cdot\left[\cos ec\left(\frac{\pi d}{2a}\right)\right] \tag{2}$$

Where a is the size of waveguide's cross section; d is the width of the gap or diaphragm window; λ_w is the wavelength in a considered square guide.

Two circuits have regulatory sections of the transmission line with electrical length θ, which is calculated by the formula [82]

$$\theta \cong \frac{2\pi l}{\lambda_w} \tag{3}$$

where *l* is the length of transmission line segment.

The guide wavelength is determined as follows [83]

$$\lambda_w \cong \frac{\lambda_0}{\sqrt{1-\left(\frac{\lambda_0}{\lambda_c}\right)^2}} \tag{4}$$

where λ_0 is the wavelength in vacuum, λ_c is critical wavelength in the rectangular waveguide.

The equivalent circuit of a square waveguide can be divided into seven simple two-port circuits (Fig. 2). They include two circuits equivalent to outer diaphragms, two circuits equivalent to central diaphragms, two circuits of regular transmission line segments of length l_1 and circuit of a regular transmission line of length l_2. These circuits are described by transfer matrices [84]:

$$[T_1]=[T_7]\cong\begin{bmatrix}T_{11} & T_{12}\\ T_{21} & T_{22}\end{bmatrix}=\begin{bmatrix}0.5(2+Y_1) & 0.5Y_1\\ -0.5Y_1 & 0.5(2-Y_1)\end{bmatrix}, \tag{5}$$

$$[T_2]=[T_6]\cong\begin{bmatrix}e^{j\theta_1} & 0\\ 0 & e^{-j\theta_1}\end{bmatrix}, \tag{6}$$

$$[T_3]=[T_5]\cong\begin{bmatrix}T_{11} & T_{12}\\ T_{21} & T_{22}\end{bmatrix}=\begin{bmatrix}0.5(2+Y_2) & 0.5Y_2\\ -0.5Y_2 & 0.5(2-Y_2)\end{bmatrix}, \tag{7}$$

$$[T_4]=\begin{bmatrix}e^{j\theta_2} & 0\\ 0 & e^{-j\theta_2}\end{bmatrix} \tag{8}$$

Where Y_1 and Y_2 are conductivity of outer and middle diaphragms; θ_1 and θ_2 are electric length of the transmission lines.

The wave transfer matrix of the waveguide polarizer is calculated as follows [85]

$$[T_\Sigma]=[T_1]\cdot[T_2]\cdot[T_3]\cdot[T_4]\cdot[T_5]\cdot[T_6]\cdot[T_7]=\begin{bmatrix}T_{11.\Sigma} & T_{12.\Sigma}\\ T_{21.\Sigma} & T_{22.\Sigma}\end{bmatrix} \tag{9}$$

Relations between the total wave transfer and scattering matrices are determined by the known

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expressions [86], [87]

$$[S_{\Sigma}]=\begin{bmatrix} S_{11.\Sigma} & S_{12.\Sigma} \\ S_{21.\Sigma} & S_{22.\Sigma} \end{bmatrix}=\frac{1}{T_{11.\Sigma}}\begin{bmatrix} T_{21.\Sigma} & |T| \\ 1 & -T_{12.\Sigma} \end{bmatrix} \tag{10}$$

From (10) we obtain expressions for the reflection coefficient [88]

$$S_{11.\Sigma}=\frac{T_{21.\Sigma}}{T_{11.\Sigma}} \tag{11}$$

From (10) we obtain expressions for the transmission coefficient [89]

$$S_{21.\Sigma}=\frac{1}{T_{11.\Sigma}} \tag{12}$$

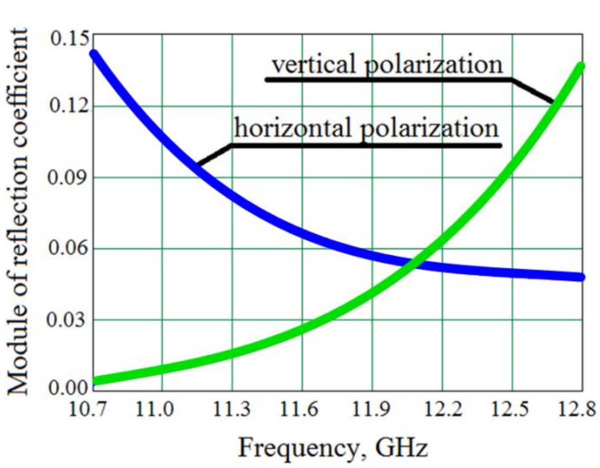
Therefore, we will further analyze the obtained coefficients.

III. Results of mathematical modeling

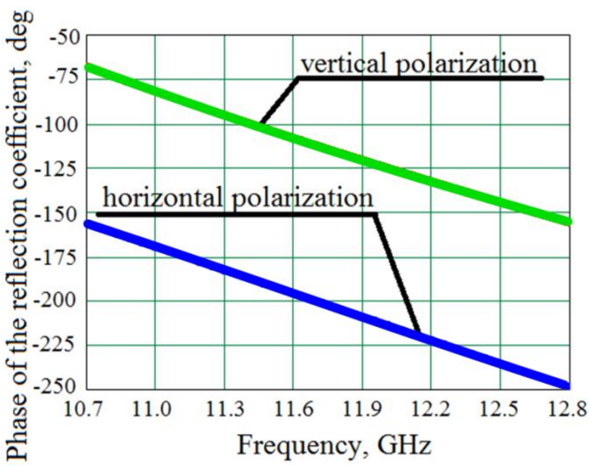
The section presents the electromagnetic characteristics of the polarizer calculated using the developed model of the polarizer. The developed guide device with four diaphragms was designed for the operating frequency range from 10.7 to 12.8 GHz.

The dimensions of the optimal waveguide convertor of polarization calculated using the proposed matrix technique and the method of finite integration are as follows. The wall size of the square waveguide is 21.6 mm. The height of the outer diaphragm is 3.91 mm, height of the central diaphragm is 2.38 mm. The distance between the central diaphragm is 7.38 mm, the distance between the outer diaphragms is 7.38 mm. The thickness of the optimal diaphragms is 1 mm.

Frequency dependences of the module and phase of the reflection coefficients for both polarizations are presented in Fig 3a, 3b, respectively.



(a)



(b)

Fig. 3. Dependences of reflection coefficient on frequency for both polarizations calculated by mathematical model: (a) module; (b) phase.

In Fig. 3a a typical behavior of the reflection of electromagnetic waves propagating inside a

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polarizer's structure versus frequency is observed for both polarizations. Namely, the module of the reflection coefficient for the horizontal polarization decreases with the increment of the frequency. On the contrary, the module of the reflection coefficient of the mode with vertical polarization creases with the increase of frequency of the fundamental electromagnetic mode.

In Fig. 3b it is possible to see that the phase of reflection coefficient for the vertical polarization is less -65º at a frequency of 10.7 GHz and for the horizontal polarization it is less than -150º at the lowest frequency of 10.7 GHz.

Fig. 4 presents the dependence the module and argument of transmission coefficient on the frequency for vertical and horizontal polarization the frequency interval 10.7–12.8 GHz.

In Fig. 4a it is observed that the module of transmission coefficient for the horizontal polarization is higher than 0.990 at a frequency of 10.7 GHz and for the vertical polarization is less 0.991 at a frequency of 12.8 GHz. In Fig. 4b it can be seen that the phase of transmission coefficient for the vertical polarization is less -50º at a frequency of 10.7 GHz and for the horizontal polarization is less 120º at a frequency of 10.7 GHz.

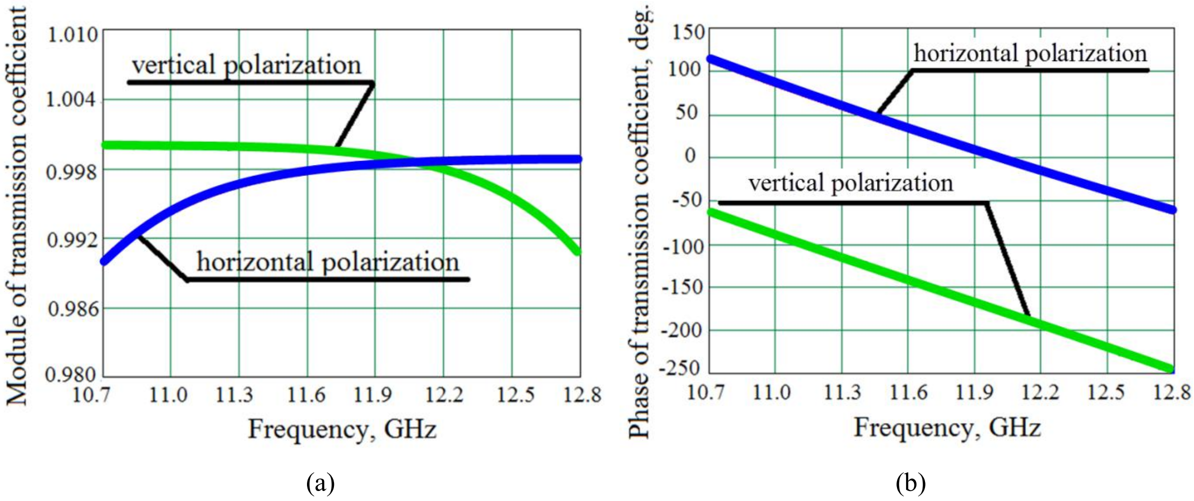


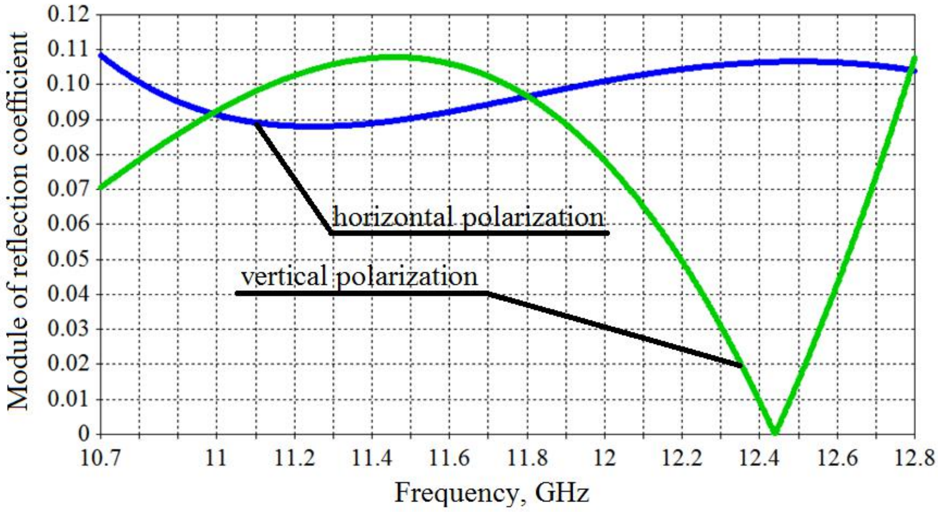
Fig. 4. Dependences of transmission coefficient on frequency for both polarizations calculated by mathematical model: (a) module; (b) phase.

Consequently, in the frequency range 10.7–12.8 GHz the optimal design of a guide polarizer with four diaphragms provides the following matching characteristics. The reflection coefficient for both polarizations is less than 0.14. The transmission coefficient for both polarizations is greater than 0.99.

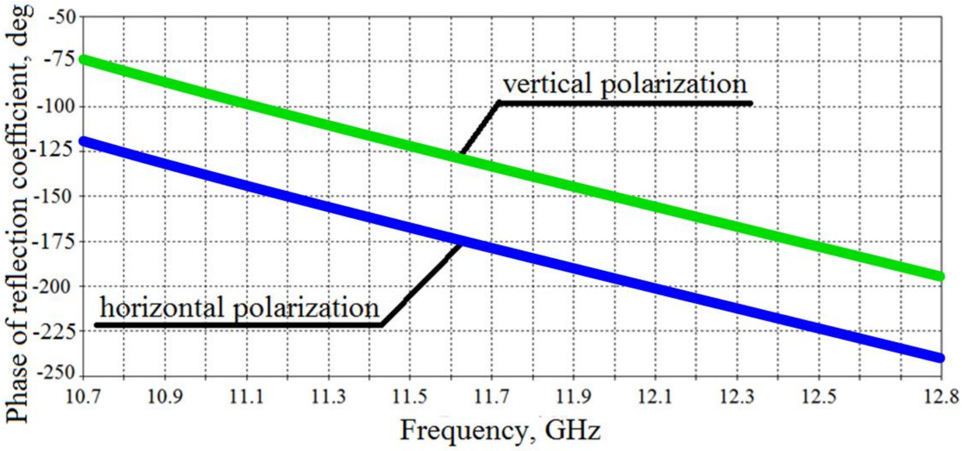
IV. Numerical simulation of the developed waveguide polarizer

This section contains the results of modeling a waveguide polarizer with four diaphragm applying the well-known electrodynamic method. As a proposed method we used the finite element technique in the frequency domain [90]-[92]. The electromagnetic characteristics of the polarizer were simulated for the frequency interval from 10.7 to 12.8 GHz using the numerical method of finite elements in the frequency domain. This technique proved its computational speed and reliability for the calculation of the electromagnetic performance of waveguide polarizers in several recent investigations [93]-[96].

In Fig. 5a it is possible to see that the module of the reflection coefficient of developed waveguide polarizer with diaphragms for both fundamental modes TE_{01} and TE_{10} is less than 0.11 in the frequency range 10.7–12.8 GHz. This result is in good agreement with the obtained before using wave matrix method. The minimum value of the modulus of the reflection coefficient of the polarizer is 0 at a frequency of 12.42 GHz. In Fig. 5b it can be seen that the phases of reflection coefficients of both polarizations decrease with the increment of frequency. Their difference is close to 50° in the whole operating frequency band 10.7–12.8 GHz.



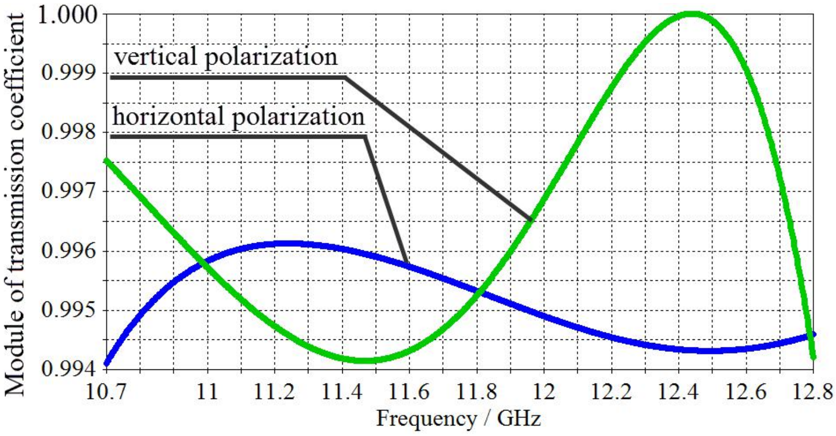
(a)



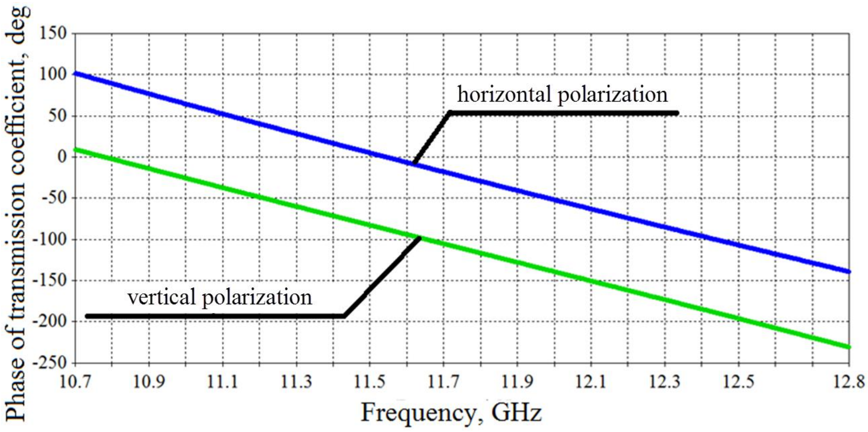
(b)

Fig. 5. Dependences of reflection coefficient on frequency for both polarizations calculated by numerical model: (a) module; (b) phase.

In Fig. 6a it can be seen that the transmission coefficient for the vertical polarization is less than 1, which corresponds to its physical sense. The peak value is reached at the frequency of 12.44 GHz. For the horizontal polarization the transmission coefficient is less than 0.997. Its maximal value is obtained at the frequency of 11.3 GHz.



(a)



(b)

Fig. 6. Dependences of transmission coefficient on frequency for both polarizations calculated by numerical model: (a) module; (b) phase.

In Fig. 6b it is possible to see that the phase of transmission coefficient for the vertical polarization is less than 10º at a frequency of 10.7 GHz and for the horizontal polarization it is less than 100º at the frequency of 10.7 GHz.

Table I presents the characteristics of the developed polarizer, which were optimized for the Ku–band for mathematical and numerical model. It demonstrates that the electromagnetic characteristics obtained using both the developed mathematical model and a numerical model of a waveguide polarizer with four diaphragms are in good agreement.

TABLE I. CHARACTERISTICS OF THE OPTIMIZED WAVEGUIDE POLARIZER

Parameters	Mathematical model	Numerical model
Maximal level of reflection coefficient	0.14	0.11
Maximal level of transmission coefficient	1	1
Minimum level of transmission coefficient	0.990	0.993
Minimum level of phase of reflection coefficient	-250º	-240º
Maximal level of phase of reflection coefficient	-65º	-75º
Minimum level of phase of transmission coefficient	-250º	-235º
Maximal level of phase of transmission coefficient	110º	100º

Consequently, it can be seen from Table 1 that all the parameters, which were calculated using the mathematical model and the numerical method, correlate with each other. This verifies the correctness of the created mathematical model. It can be widely applied for fast estimation of modules and arguments of the scattering parameters of polarizers, rotators, filters and other microwave devices based on discontinuities located in waveguides.

V. CONCLUSIONS

In this article we have developed a model of a microwave square polarizer with four diaphragms. Using the proposed model the electromagnetic parameters of a polarizer were optimized in the frequency range 10.7–12.8 GHz. The developed device ensures a reflection coefficient modulus of less than 0.14 for both linear polarization. The modulus of the transmission coefficient of a polarizer is more than 0.99 for both polarizations.

The results, which were obtained by the wave matrix model, can be used to develop and optimize waveguide polarizers with diaphragms. Further theoretical researches should focus on the creation of mathematical models for the devices with a larger number of diaphragms, which will provide better characteristics of the reflection and transmission coefficients. In addition, the presented structures can be effectively used for designing of new waveguide filters for various purposes.

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