Electromagnetic Performance of Waveguide Polarizers with Sizes Obtained by Single-Mode Technique and by Trust Region Optimization

Stepan Piltyay[1], Andrew Bulashenko[1], Yelyzaveta Kalinichenko[1], and Oleksandr Bulashenko[2]

[1]Department of Radio Engineering, National Technical University of Ukraine “Igor Sikorsky Kyiv Polytechnic Institute”, Kyiv, Ukraine
[2]Electromechanical Department, Ivan Kozhedub Shostka Professional College of Sumy State University, Shostka, Ukraine

Corresponding author: Stepan Piltyay (e-mail: crosspolar@ukr.net).

ABSTRACT Modern wireless networks, stationary terrestrial, and satellite systems use many modern technologies to increase communication channels’ information capacity. They save limited frequency resources. The polarization signal processing is applied to reuse the allocated frequency bands in satellite communications. Using circularly polarized electromagnetic waves, which transmit useful signals, reduces fading effects and eliminates disadvantages introduced by multipath propagation interferences. In this case, the distortion levels for signals with an odd number of electromagnetic wave reflections in the receiving antenna systems will be reduced to the thresholds of their cross-polarization isolation. Besides, in the case of orthogonal polarization usage, the achieved information capacity of the applied wireless communication channel multiples almost by a factor of two. The type of polarization of the used electromagnetic wave strongly determines the peculiarities of the process of its propagation in the space or transmission line. Polarization signal processing is frequently carried out in horn feed systems of the reflector antennas. Such feed networks and systems allow for transmitting and receiving signals with several kinds of polarization simultaneously. The fundamental element of dual circular polarization antenna feed networks is a waveguide polarization duplexer. The phase, isolation, and matching characteristics of a polarization converter strongly influence the entire reflector antenna system’s functionality and polarization discrimination possibilities. Therefore, the development and optimization of the characteristics of waveguide polarizers for satellite communication antennas is a crucial technical problem that fast and accurate methods must solve. This research is carried out to compare the electromagnetic performance of waveguide polarizers with sizes obtained using a fast single-mode technique and by a more accurate trust-region optimization method. The results for differential phase shift, level of voltage standing wave ratio, ellipticity coefficient, and cross-polarization discrimination are shown and discussed.

INDEX TERMS electromagnetic simulation; microwave engineering; polarizer; waveguide polarizer; optimization; single-mode technique; trust region method; waveguide components; circular polarization.

I. INTRODUCTION

RADIO engineering systems apply various technical solutions to extend transmitted, received and processed volumes of useful information. For instance, state-of-the-art mobile 5G communication systems and networks use well-known D2D, M2M and OFDM technologies [1–3] and spatial diversity technologies with the application of specific antenna arrays [4] to increase the information capacity of wireless channels. On the other hand, the most popular engineering solution in satellite and some wireless communication systems is the polarization separation of signals or antennas reconfiguration, which allows doubling the transmitted information volumes within the same frequency band [5]. In addition, antennas with circular polarization are actively applied in modern vehicular communications [6] and portable high-power microwave systems [7]. The applied antenna system must contain specific types of microwave waveguide devices [8, 9] to provide a possibility to operate at circular polarization. Namely, these devices are orthomode duplexers [10–12] and waveguide polarization converters [13, 14]. One of the common types of waveguide polarization transforming devices is polarizers with conducting metal septum plates. The main benefit of this kind of polarization transformer is its compact structure, which combines the functionality of an orthomode duplexer and the polarizer itself. The common disadvantage of this type of polarization transforming device is its narrow operating frequency band, limiting its utilization in modern satellite systems. In [15], it was shown that the fractional bandwidth of a septum-based polarizer could reach only 20% if the antenna feeding network has to provide both isolation between ports higher than 25 dB and cross-polarization isolation of more than 30 dB.

The diaphragm-based waveguide polarizers [16–20] distinguish in their structure and use wider fractional bandwidths with better electromagnetic characteristics. In broadband antenna systems with double polarization, the waveguide polarization transformer with diaphragms combines with an orthomode transducer [21], which complicates the antenna feed structure. On the other hand, using a waveguide polarizer with diaphragms, we can ensure much better performance in the same operating frequency band compared to the polarization converter with a longitudinal septum. In addition, the design of the waveguide polarizer with diaphragms has an axial symmetry C2 and two mirror planes of symmetry that lowers the occurrence of possible polarization distortions and higher electromagnetic modes excitation and simplifies the fabrication process using efficient milling and CNC technologies.

Authors of [22, 23] developed an analytical single-mode method for modeling waveguide polarization converters' characteristics by conducting transversal diaphragms based on single-mode wave matrices of scattering and transmission. A waveguide polarizer with two diaphragms in the frequency range 7.4–8.5 GHz was developed and optimized in [24]. In this band, it provided a differential phase shift of 90º ± 8º. The ellipticity coefficient of the polarization converter was less than 1.6 dB. Its cross-polarization discrimination was less than 21.5dB.

Waveguide polarizers with different number of diaphragms and posts were developed for satellite communication systems [25]. The article [26] proposes the design of a waveguide polarizer with a higher-order input mode. Relative bandwidth of 12.9% with an ellipticity factor of 3 dB was achieved. In [27], a modified analytical method of synthesis for modeling and designing new polarizers based on waveguides with diaphragms is presented. The method was tested to develop a polarizer for a frequency range from 3.4 to 4.2 GHz. Polarizer provided a differential phase shift of 90º ± 4.0º. The ellipticity coefficient was less than 1.6 dB. Cross-polarization discrimination was less than 28 dB.

In [28], a new simple mathematical method for calculating the characteristics of waveguide sections with diaphragms and antiphase pins was proposed. The suggested sections can be used to develop new waveguide filters, phase shifters, and polarization processing devices. The proposed designs can be adjusted by changing the length of the pins. Two waveguide sections were created with the differential phase shifts of 30° ± 0.7° and 45° ± 1.75°. Adjustable waveguide polarizers were developed based on these effective structures [26, 29]. These guide devices provided good electromagnetic characteristics in the operating satellite X-band 7.7–8.5 GHz. The differential phase shift of polarizers lied within the range of 90º±3.25º. The ellipticity coefficient was less than 0.5 dB. Cross-polar discrimination was higher than 31 dB. The disadvantage of developed polarizers is the large size and complexity of their design.

A better symmetry of structure and less polarization distortions can be obtained in waveguides with better axial symmetry. Typical examples of waveguides with such symmetry are ridged waveguides [30–33], based on which dual-band coaxial and other orthogonal mode transducers and polarization duplexers are designed [34].

In [35], a new design of a four-ridged orthomode converter for the C-band is proposed. The structure consists of two sets of identical orthogonal ridges placed in a circular waveguide. The device provides a reflection coefficient of not more than −15 dB at a cross-polarization level of −40 dB in the frequency band 3.4–4.2 GHz. The design of a polarizer with two diagonal ridges and an output diaphragm based on a square waveguide segment was proposed in [36]. This polarizer supports a frequency bandwidth of 13%. The obtained ellipticity coefficient does not exceed 1 dB. The cross-polarization isolation is greater than 27 dB.

The authors of the article [37] developed a numerical algorithm to analyze and optimize broadband polarizers. The design of such devices consists of symmetrically placed rectangular ridges in a coaxial waveguide. It is proposed to use an approach based on a step-by-step approximation. Factors that influenced on reliability and accuracy of calculations are identified. The authors of the researches [30–32] presented a mathematical model for sectoral coaxial ridges waveguides analysis. The considered waveguides are used in dual-band polarization processing devices. Using integral equations method, ridged coaxial waveguides mathematical models were obtained in [33]. The maximum ratios of the cutoff frequencies of the two lowest modes of coaxial ridges waveguides were found. Using transmission lines of this kind, the new double-band coaxial orthomode duplexers were designed in several research works [34, 35]. In [38], the new feed network of the antenna based on a cylindrical waveguide is developed. This guide system has a built-in polarizer structure that provides symmetrical patterns of circular polarization radiation. The design consists of nine pairs of channels that provide specifically polarized electromagnetic wave formation. This antenna feed system offers an ellipticity factor of 1.2 dB at frequencies from 79.5 GHz to 88 GHz. The main disadvantage of such waveguides is the complexity of their manufacturing process.

Therefore, waveguide polarization converters can be simulated using fast single-mode wave matrix approaches [22–24]. On the contrary, the optimization of characteristics of guide polarizers can be carried out by the trust-region method [25] with more rigorous numerical schemes, including FEM or FDTD [39]. The current study aims to compare the results provided by these two possible approaches. For this purpose, we will consider the performance of a waveguide polarization converter with diaphragms and optimize its electromagnetic characteristics for the satellite operating frequency range of 10.7–12.8 GHz.

II. WAVEGUIDE POLARIZER'S MODEL ACCORDING TO THE SINGLE-MODE WAVE MATRIX TECHNIQUE

The finite integration method [39] was used to model and optimize the characteristics of a polarizer based on a square waveguide with three diaphragms. This section presents the results of numerical simulations and optimization. Fig. 1 shows the internal structure of a square waveguide polarizer with three diaphragms. Designations of all sizes of a design are also shown in Fig. 1.

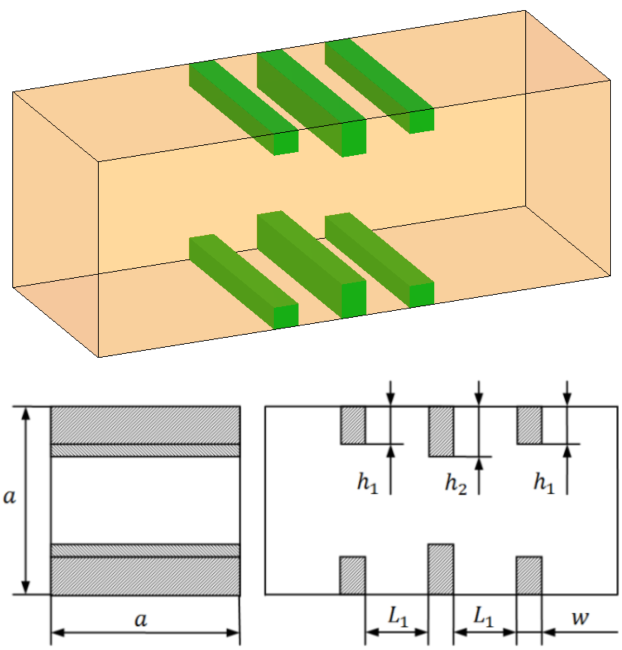

FIGURE 1. Structure of a square waveguide polarizer with three diaphragms

Using the theoretical method of equivalent microwave circuits and the method of wave matrices of scattering and transmission [23], the expressions of the elements of the scattering matrix of a waveguide polarizer with three diaphragms were obtained. The electromagnetic characteristics of the developed waveguide polarizer were expressed through these matrix elements.

The characteristics of device polarization processing strongly influence on characteristics of the whole antenna system. The main electromagnetic characteristics include phase, matching, and polarization parameters. The electromagnetic characteristics of the polarizer are the operating frequency band, the peak level of the voltage standing wave (LVSW) for both polarizations, the differential phase shift, the ellipticity coefficient, and the cross-polar discrimination (CPD).

The differential phase shift at the output of the polarizer is determined by the expression

$$\Delta\varphi = \varphi_L - \varphi_C = \arg(S_{21\Sigma L}) - \arg(S_{21\Sigma C}), \quad (1)$$

where $S_{21\Sigma L}$ and $S_{21\Sigma C}$ are elements of the general scattering matrix in the case of inductive and capacitive diaphragms. This difference shows relative phase shift between fundamental electromagnetic modes with two perpendicular polarization states. Proximity of the differential phase shift to 90° allows to obtain a device that converts linear polarization into circular or vice versa.

LVSW is defined by an analytical expression

$$\mathrm{LVSW} = [1 + |S_{11}|]/[1 - |S_{11}|]. \quad (2)$$

where S_{11} stands for the reflection coefficient's magnitude. According to the definition, LVSW is the ratio of maximal field's amplitude to its minimal value along the transmission line. In the point of maximum, a constructive interference of an incident and a reflected wave is observed. In this case, in normalized amplitude values we obtain a sum $1 + |S_{11}|$. On the other hand, a destructive interference of an incident and a reflected wave is observed in the point of minimum. Therefore, minimal amplitude corresponds to the difference $1 - |S_{11}|$. Writing the ratio of indicated values, we obtain formula (2).

The following formula can determine the coefficient of ellipticity:

$$k = 10\log_{10}\left(\frac{A^2+B^2+\sqrt{A^4+B^4+2A^2B^2\cos(2\Delta\varphi)}}{A^2+B^2-\sqrt{A^4+B^4+2A^2B^2\cos(2\Delta\varphi)}}\right), \quad (3)$$

where $A = |S_{21\Sigma L}|$, $B = |S_{21\Sigma C}|$. In [16] the authors derived the formula (3). It takes into account output amplitudes of electromagnetic waves with perpendicular polarization states and differential phase shift between them. When the amplitudes are equal values, and phase shift is 90°, the coefficient of ellipticity is 0 dB. In this case, a perfect transformation between linear and circular polarization states is ensured. Higher values of the coefficient of ellipticity indicate deviation of the differential phase shift from 90° and/or inequality of the output amplitudes.

The expression for calculating the CPD will be as follows:

$$\mathrm{CPD} = 20\lg\left(\frac{10^{0{,}05k}+1}{10^{0{,}05k}-1}\right). \quad (4)$$

The initial geometric dimensions of the polarizer are determined by the suggested in [25] method. Since the polarizing device operates in the operating frequency range of 10.7–12.8 GHz, the waveguide's wavelength ranges from 14 mm to 29 mm. The average frequency of the band is 11.75 GHz. At this frequency, the wavelength in the waveguide is determined by this expression

$$\lambda_w = \frac{c/f_0}{\sqrt{1-\left(\frac{c/f_0}{2a}\right)^2}}. \quad (5)$$

where c designates light's velocity in vacuum, f_0 is a central frequency of the operating range, a is a transversal size of the square waveguide's wall.

The initial length of the distance between the diaphragms is determined as follows

$$L = 0.25\lambda_w. \quad (6)$$

This initial value ensures good matching due to destructive interference of two fundamental modes, which are reflected from two adjacent diaphragms in a waveguide.

III. NUMERICAL RESULTS AND OPTIMIZATION OF THE WAVEGUIDE POLARIZER BY TRUST-REGION METHOD

Optimization is carried out according to the trust-region method [25]. The method works in a way that first determines a small region of dimensions near the current best solution, in which a mathematical model allows to some extent approximate the goal functions. Optimal values of electromagnetic characteristics of a polarizer (including LVSW and CPD) are goal functions of the optimization process. After the determination of initial values, the method performs a step in dimensions according to the model depicts in the region. The size of the step is determined before the improvement of direction. If the values of goal function improve, then the procedure continues in the same direction. In the other case, the direction or step size must be altered.

There are some peculiarities of the polarizer's performance optimization by the trust-region method. First, we change the size of the wall of a waveguide and reach the value of the phase derivative on the frequency. Then we change the height of the diaphragms h_1 and h_2 to achieve the differential phase shift of 90º or make it closer to this value. After this, we change the distance between the diaphragms L to achieve the minimum values of VSWR for vertical and horizontal polarization states.

Fig. 2 shows the dependences of LVSW of the non-optimized and optimized polarizer with three diaphragms on the frequency for both polarizations in the operating range of 10.7–12.8 GHz. Fig. 2 shows that the maximum value of LVSW for both polarizations is 2.34 and is reached at the lowest frequency of the operating Ku-band 12.8 GHz in the case of the non-optimized polarizer. Fig. 2 shows that the maximum value of LVSW for both polarizations is 2.03 and is achieved at the lowest frequency of the operating Ku-band 10.7 GHz in the case of an optimized polarizer.

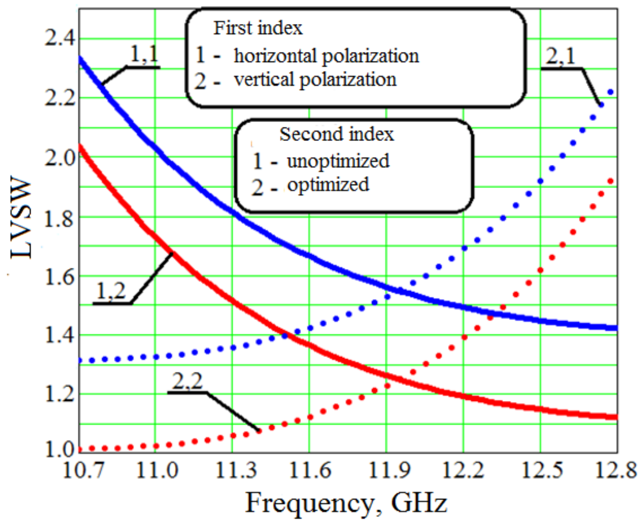

FIGURE 2. Dependences of LVSW on frequency for a square waveguide polarization converter with three diaphragms

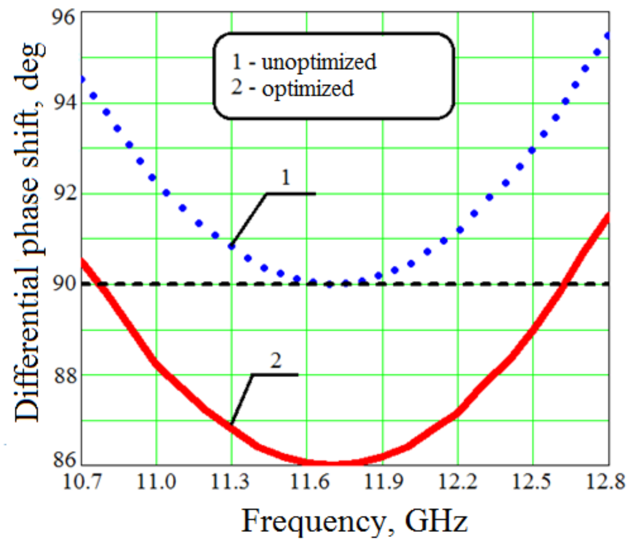

FIGURE 3. The differential phase shift of a square waveguide polarization converter with three diaphragms

In Fig. 3, we can see that for a non-optimized polarizer, the differential phase shift varies within 90° ± 5.5° in the operating frequency range. At 11.7 GHz, the differential phase shift becomes 90°. From Fig. 2 for the optimized polarizer, it can be seen that the differential phase shift is equal to 90° at frequencies of 10.76 GHz and 12.63 GHz. In the operating Ku range of 10.7–12.8 GHz, the differential phase, rectangular optimized waveguide polarizer shift with three diaphragms varies from 86° to 91.6°. The maximum deviation of the differential phase shift from 90° is 4° and is carried out at a frequency of 11.7 GHz, which is close to the central frequency of the operating Ku-band.

The frequency dependences of the differential phase shift and ellipticity coefficient for non-optimized and optimized polarizers, based on a rectangular waveguide with three diaphragms, are shown in Fig. 3 and Fig. 4, respectively. Fig. 4 shows that in the operating frequency band 10.7–12.8 GHz, the ellipticity coefficient of the optimized square waveguide polarizer with three apertures is less than 0.6 dB.

As shown in Fig. 5, the corresponding polarizer CPD does not fall below the level of 29.5 dB. The maximum of the ellipticity coefficient (as well as the lowest CPD) is observed at the frequency of 11.7 GHz, which corresponds with high accuracy to the frequency of the maximum deviation of differential phase shift of the polarizer from 90°.

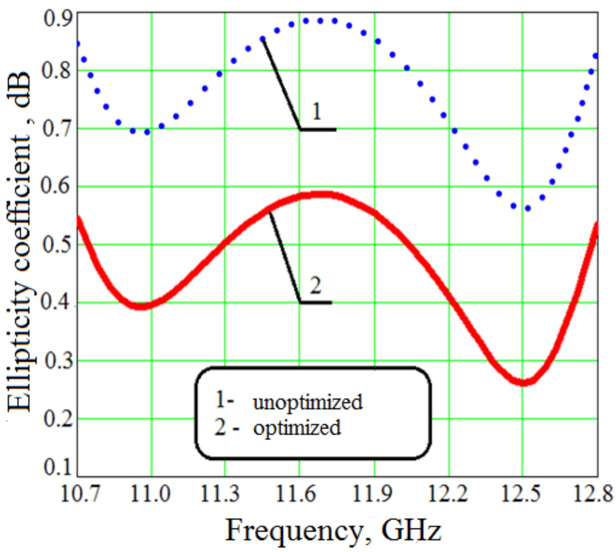

FIGURE 4. Ellipticity coefficient vs. frequency for the square waveguide polarizer with three diaphragms

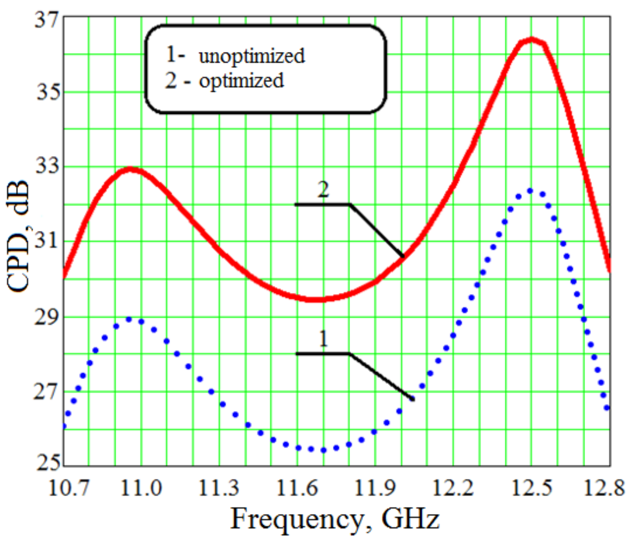

FIGURE 5. Ellipticity coefficient vs. frequency for the square waveguide polarizer with three diaphragms

Thus, due to optimization using the trust-region scheme, the electromagnetic characteristics of the developed square waveguide polarizer with three diaphragms were improved. Comparisons of these characteristics are summarized in Table 1.

TABLE I. COMPARISON OF THE CHARACTERISTICS OF NON-OPTIMIZED AND OPTIMIZED WAVEGUIDE POLARIZERS WITHIN THE OPERATING KU-FREQUENCY RANGE

Characteristic	*Single-mode technique*	*Optimized by the trust-region method*
Differential phase shift, deg	90° ± 5.5°	90° ± 4.0°
Maximum VSWR	2.34	2.03
Coefficient of ellipticity	0.9 dB	0.6 dB
Minimum CPD	25.5 dB	29.5 dB

As can be seen from Table 1, the optimized characteristics of the polarizer have been improved.

All internal dimensions of optimized polarizer designs, based on a square waveguide with three diaphragms for operating Ku-band 10.7–12.8 GHz, are shown in Table 2.

TABLE II. DIMENSIONS OF NON-OPTIMIZED AND OPTIMIZED WAVEGUIDE POLARIZERS

Size	*Single-mode technique*	*Optimized by the trust-region method*
Waveguide wall size	21.5 mm	21.6 mm
The height of the middle diaphragm	3.12 mm	3.86 mm
The height of the outer diaphragms	2.08 mm	2.45 mm
The distance between the diaphragms	5.92 mm	4.92 mm
The thickness of all diaphragms	2 mm	2.79 mm

When a larger number of diaphragms is used in polarizer design, the differential phase shift introduced by each diaphragm becomes smaller because the total differential phase shift at the output of the polarizer must be close to 90° for each of the considered designs. This reduces the height of the diaphragm as they increase in number. In addition, reducing the height of the aperture improves the alignment of the polarizer structure.

IV. COMPARISON OF NUMERICAL OPTIMIZATION RESULTS FOR PROPOSED SINGLE-MODE AND FEM ELECTRODYNAMIC MODELS

To verify the correctness of the obtained results, we compared a known electrodynamic method of finite integration in the frequency domain [39]. To do this, we compare the electrodynamic characteristics obtained by our method with the characteristics obtained by this electrodynamic method.

Fig. 6 presents the matching and phase characteristics of the optimized waveguide polarizer by the proposed and electrodynamic methods in the operating range of 10.7–12.8 GHz. In Fig. 6, the dependences of LVSW of the optimized polarizer are shown for vertical and horizontal polarizations in the operating range of 10.7–12.8 GHz. It can be seen that the maximum value of LVSW for both polarization states is 2.03 and 2.06 for the proposed and electrodynamic methods, respectively. Consequently, the results are in good agreement.

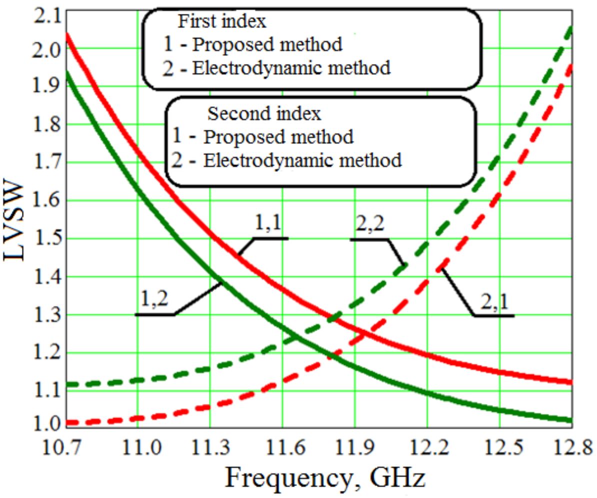

FIGURE 6. Dependences of LVSW on frequency for a waveguide polarizer

Fig.7 illustrates the dependence of differential phase shift of the optimized polarizer on the frequency in the operating Ku-band for both methods. It should be noted that the differential phase shift varies between 90°±4° and 90°±3° for the proposed and electrodynamic methods, respectively, throughout the operating frequency range.

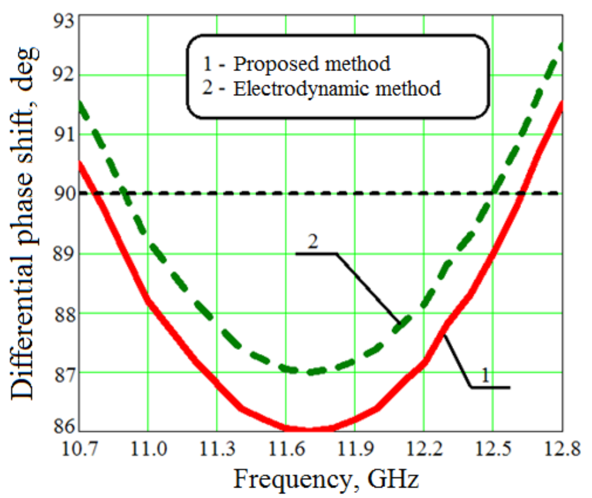

FIGURE 7. The differential phase shift of waveguide polarizer with three diaphragms

The frequency dependences of the ellipticity coefficient and CPD of a polarizer based on a square waveguide with three diaphragms for both methods in the operating Ku-range are presented in Fig. 8 and Fig. 9, respectively.

From Fig. 8, we see that in the operating frequency band 10.7–12.8 GHz, the ellipticity factor of the optimized polarizer is less than 0.6 dB for the proposed method and less than 0.5 dB for the electrodynamic method. As shown in Fig. 9, the corresponding CPD of the polarizer exceeds 29.5 dB for the proposed method and exceeds the level of 30.5 dB for the electrodynamic method.

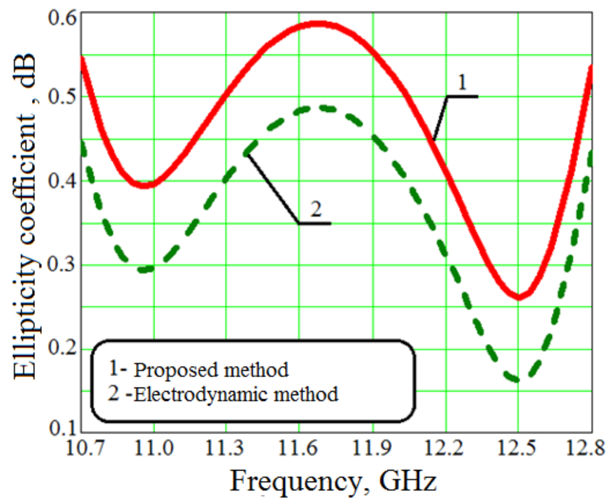

FIGURE 8. Ellipticity coefficient vs. frequency for the waveguide polarizer

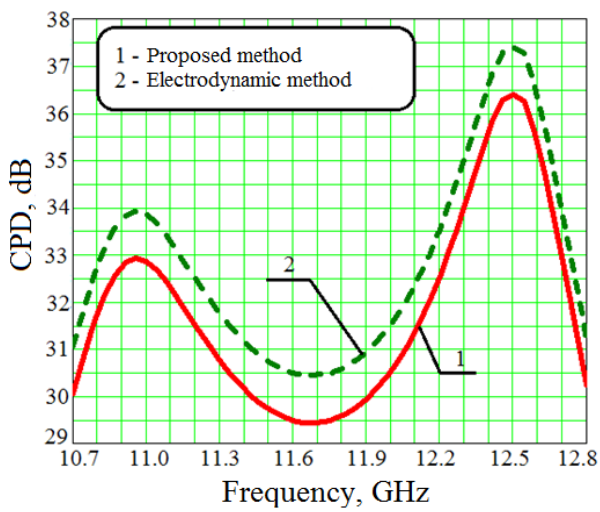

FIGURE 9. CPD vs. frequency for the waveguide polarizer with three diaphragms

Electromagnetic characteristics of the optimized polarizer based on a square waveguide with three diaphragms obtained by the proposed method and the electrodynamic method are presented in Table 3.

TABLE III. COMPARISON OF THE CHARACTERISTICS OF A POLARIZER OBTAINED BY THE PROPOSED AND FEM ELECTRODYNAMIC METHODS IN THE WORKING KU-RANGE

Characteristic	*The proposed single-mode method*	*FEM electrodynamic model*
Differential phase shift	90° ± 4.0°	90° ± 3.0°

Characteristic	*The proposed single-mode method*	*FEM electrodynamic model*
Maximum LVSW	2.03	2.06
Coefficient of ellipticity	0.6 dB	0.5 dB

From Table 3, we see that the electromagnetic characteristics of the proposed single-mode method and the FEM electrodynamic method have slight differences.

Therefore, the developed polarizer based on a square waveguide with three diaphragms provides a maximum level of LVSW below 2.06. The ellipticity coefficient does not exceed 0.6 dB, and the CPD is higher than 29.5 dB. Consequently, the developed waveguide polarizer provides good matching and polarization characteristics in the operating Ku-band.

V. CONCLUSIONS

This paper compared the electromagnetic characteristics of developed and optimized polarizers based on a square waveguide with three diaphragms. Two theoretical methods were applied: a single-mode wave matrix technique and a trust-region optimization with a finite element simulation scheme.

Modeling by the single-mode technique showed that the developed waveguide polarizer provides a voltage standing wave ratio of less than 2.03. The differential phase shift is 90 ° ± 4.0 °. The coefficient of ellipticity is less than 0.6dB. The CPD is higher than 29.5 dB.

To verify the proposed method, a comparison was made with the electromagnetic characteristics of the developed device, which were obtained using the FEM electrodynamic model. Obtained results are in good agreement and prove that the developed waveguide polarizer provides effective polarization and matching characteristics. The polarization converter can be applied in modern satellite, radar, and navigation systems with orthogonal circular polarizations for the operating Ku-band.

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