Comparative Analysis of Compact Satellite Polarizers Based on a Guide with Diaphragms

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ABSTRACT In this article we carry out the comparative analysis of new compact satellite polarizers based on a square guide with diaphragms. The main electromagnetic parameters of the developed microwave guide devices with various amount of diaphragms were obtained within the satellite frequency interval from 10.7 GHz to 12.75 GHz. Waveguide polarization converters with different amount of diaphragms from 3 to 5 have been designed and optimized. The main parameters of the presented polarizer were calculated applying the numerical method of finite integration in the frequency domain. Optimization of the electromagnetic parameters of the developed waveguide devices was carried out using the finite elements method in the frequency domain. As a result, sizes of the guide polarizer design have been optimized for the provision of improved polarization and phase parameters. The performed analysis showed that a waveguide polarizer with five diaphragms has the best electromagnetic parameters. The developed compact polarizer with five diaphragms based on a square guide provides a minimum deviation of the output phase difference from 90 degrees and high level of isolation between linear polarization over the entire operating frequency range. Presented in the article compact waveguide polarization converters can be applied in modern satellite systems, which require efficient polarization transformation and separation of signals.

INDEX TERMS waveguide polarizer, diaphragms polarizer, microwave devices, waveguide components, electromagnetic simulation, circular polarization, output phase difference, isolation of linear polarization.

I. INTRODUCTION

THE allocation of operating frequency bands to users of different systems and appliances is strictly regulated and monitored. Due to this reason the information capacity of wireless mobile, satellite and other communication channels is limited. Therefore, nowadays the economy and management of this limited and expensive resource is of crucial importance. This leads to the occurrence of radio engineering techniques of the repeated utilization of the allocated to user frequency range. One of the most promising methods of frequency reuse is achieved in the antennas and systems applying simultaneous operation at two linear or circular orthogonal polarizations with high isolation between the independently transmitted signals. This effective radio engineering solution allows to double information capacity of the applied wireless channel with an allocated frequency band.

The impact of polarization type on the process of electromagnetic waves' propagation is of critical importance [1–3]. The fading effect in wireless systems can be reduced in the case of application of circular polarization type of the transmitted signals [3–10]. The signals, which are reflected from the environmental objects odd times, will possess orthogonal polarization with respect to the transmitted one. In this case the interfering electromagnetic waves will be reflected by the receiving antenna of the wireless system. In addition, the utilization of circular polarization kind in space telecommunications allows to transmit and receive signals from rotating around the communication line direction satellites and aircrafts [3–5]. Besides, the influence of Faraday effect in the atmosphere on wireless transmission quality is negligible for the signals transmitted by circularly polarized waves [1–5]. This peculiarity plays an important role in the telemetry and radio control of ballistic missiles.

A waveguide polarizer is a device of antenna feed network, which converts electromagnetic modes with circular polarizations into linearly polarized or vice versa. Consequently, this waveguide component determines main parameters of the antenna system, such as output phase difference, reflection factor, transmission factor and isolation of linear polarizations (ILP).

II. Designs of modern waveguide polarizers

A waveguide polarizer with longitudinal septum is the most frequently used kind of polarization converters and dividers [11–25]. The main benefit of this polarizer consists in its compact structure, which combines the functions of an orthogonal mode selector and polarization converter. The disadvantage of a polarizer with longitudinal septum is its narrow operating frequency band. Recently, a new septum polarizer was proposed in [11] for the application in an antenna without mechanical switching between right and left hand circular polarizations (LHCP and RHCP). In [12] a model of a new septum polarizer with stepped ridge transitions in a rectangular waveguide was proposed. The numerical analysis of a septum polarizer was carried out using computer simulation in [13]. A compact septum polarizer with two steps in the frequency range 8–9 GHz is presented in [16]. Another design of a waveguide septum polarizer with a cone-shaped form was proposed in [17].

In [18] it was found by the authors that the relative bandwidth of a septum polarizer can reach only 20% if the isolation between rectangular waveguide ports is higher than 25 dB and ILP is higher than 30 dB. Another septum polarizer with an integrated transition from a square to a circular guide was tested in [19]. Measured characteristics correlate with values obtained by CST Microwave Studio in the band of 18.5–21.5 GHz. In [20] a broadband septum polarizer was developed for new antenna system operating in the frequency band 8–12 GHz. It provides the simultaneous operation at two orthogonal circular polarizations. In [21] a septum polarizer design was proposed for the range 27.5–30.0 GHz. The longitudinal profile of the septum was formed using Legendre polynomials. The new design of a compact waveguide duplexer that operates at a frequency of 225 GHz is presented in [22]. It applied a septum polarizer to operate at circular polarization. Developed guide device provides 30 dB isolation over a 10% bandwidth. In [23, 24] the authors presented a compact polarizer with a stepped thickness septum for the range of 7.7–8.5 GHz. The minimum cross-polarization isolation value is 30 dB. A new polarizer with a bandwidth of 37.8% based on a triangular waveguide was proposed in [25]. This polarizer was developed for two different frequency ranges 18–26 GHz and 75–110 GHz. Its ellipticity coefficient does not exceed 1.3 dB.

Another frequently used device for polarization transformation is a guide polarizer with diaphragms [26–43]. It allows to obtain better performance in wider relative bandwidths. The main disadvantage of the diaphragm-based polarizer design consists in greater complexity of the resulting antenna feed network, which must contain separate polarization converter and an orthogonal modes selector [26]. The benefit of a polarizer with diaphragms is its axial mirror symmetry with respect to two perpendicular planes, which improves the polarization purity, decreases higher modes excitation and allows simple fabrication by the highly accurate and efficient CNC milling technology.

In [27] researchers carried out the analysis of main polarizer's characteristics sensitivity to the alteration of its geometrical dimensions. The process of optimization of a polarizer based on a circular waveguide with elliptical diaphragms is presented in [28]. The authors of [29] developed a new polarizer-rotator with diaphragms based on a square waveguide. A developed polarizer with six diaphragms provides a phase shift of 180º ± 2º in the operating band of 12.8–14.2 GHz. In [30, 31], the authors proposed a method for the development of waveguide polarizers with diaphragms. As a result, Ka-band polarizers with a bandwidth of 10% were developed. They provided an excellent output phase difference of 90º±1º.

A new method for the development of dual-band polarizers based on a square waveguide with diaphragms was proposed in [32]. As a result, a new guide polarizer was designed for the operation in 20.8–21.2 GHz and 30.6–31.0 GHz bands using the HFSS software. Another design of a dual-band waveguide polarizer was developed in [33]. This guide polarizer was designed for the simultaneous operation in two bands: 25–26 GHz and 34–35 GHz. In both bands it provides an ellipticity factor of less than 0.4 dB. In [34] a design of a waveguide polarizer with diaphragms was proposed for the antenna feed system operating in the satellite C-band. The field theory of modes propagating in a diaphragm polarizer for satellite applications is considered in [36]. A comparison of theoretical and simulated characteristics was made in the research. In [37] a new design of a broadband diaphragm polarizer for the operating frequency band 3.4–4.8 GHz is presented. The developed polarizer provides an output phase difference of 90º ± 2.5º with a maximum reflection factor of −33 dB. Another efficient design of a waveguide polarizer for the frequency range 85–115 GHz was proposed in [38]. Designed polarizer provides an output phase difference of 90º ± 3.3º at the output port with a maximum value of the ellipticity factor of 0.6 dB. In [40] the authors developed a new feed network for the reflector antennas operating in the C-band 3.4–4.8 GHz. Voltage standing wave ratio of the network did not exceed 1.14. In [41–43] several designs of polarizers based on a square guide with a different number of diaphragms were developed for use in antennas for satellite communications.

Higher order of the structure's symmetry and lower higher-order modes excitation can be achieved using the guides with the symmetries of C4 or C∞ kinds. These highly symmetrical designs are based on the guides of sectoral [44, 45] and quad-ridged types [46, 47]. Several kinds of polarization converters and orthogonal modes selectors based on mentioned guides were suggested in [48–54]. The drawback of sectoral and quad-ridged guides is the complexity of their fabrication process, the impossibility of fine tuning and calibration.

In [55–60] various guide polarizers with diaphragms in the form of slots in circular and square waveguides are presented. In addition, the phenomenon of optical activity is suggested for the development of novel polarizers with diaphragms in the form of slots in a rectangular waveguide [55, 56]. The designs of such polarizers contained four slot-based diaphragms. In [57] a design of a polarizer based on a structure with two-sided symmetry is presented. A new tunable design of a polarizer based on a circular slot waveguide was proposed in [58]. The design of a polarizer with diaphragms in the form of slots was presented in [60]. The structure is formed by resonant diaphragms with rectangular slots. This design provided a phase shift of 90° for various operating frequency ranges.

The new designs of polarizers with posts in circular and square waveguides are presented in [61–68]. The results of experimental and numerical simulation of characteristics of cylindrical posts in circular and rectangular waveguides are published in [61, 62]. It has been shown that it is possible to expand the range by increasing the number of posts and changing their lengths. Some other research [63, 64] studied the scattering characteristics of a circular and rectangular waveguides loaded by posts. In [65] the scattering characteristics of a section of a rectangular waveguide with opposite-located posts were investigated. The design of a tunable posts-based guide polarizer for the Ku-band was proposed in [66]. Adjustment is accomplished by installing a pair of movable metal posts. In [67] the design of a compact mode converter using rectangular metal posts in a circular waveguide is presented. The design of a waveguide resonator with posts was proposed in [68]. In [69] a technique for designing of waveguide polarizers with cylindrical posts is presented. A waveguide polarizer section with a combined structure of posts and diaphragms was proposed in [70]. This section can provide differential phase shift of 45º and 90º. Other designs of tunable polarizers based on a guide with diaphragms and posts are presented in [71, 72]. A fast technique for designing of polarizers with cylindrical posts was proposed in [73].

In [74–79] the authors developed various theoretical methods for the calculation of characteristics of guide polarizers using the analysis of electromagnetic fields, wave scattering matrices, and approximate approximation techniques for coaxial and ridged structures. The parametric synthesis of square polarizers with diaphragms was performed in [80–85]. In [80, 81] a new method was developed to analyze polarizers with diaphragms based on microwave scattering and transmission matrices. The main electromagnetic parameters of the device were expressed through the elements of the matrices. In [82] the authors developed a method for analysis of waveguide polarizers based on equivalent circuits. In [83] a parametric analysis of guide polarizer for the operating range 3.4–4.2 GHz was carried out. The optimization and development of a polarizer based on a square guide with two diaphragms with the account of their thickness was carried out in [84, 85].

The designs of polarizers for the millimeter wave range of modern 5G systems are presented in [86–92]. In [86] it was proposed to use a horn antenna with a built-in waveguide polarizer to obtain broadband polarized radiation mode. In [87, 88] circularly polarized antenna arrays based on a guide polarizer are presented. A new polarizer for circularly polarized finite-radiation antennas in 5G mobile devices was proposed in [91]. The developed polarizer has a partition integrated into the substrate. The purity of polarization is improved by the application of metallized slots. The 29 GHz polarizer maintains an ellipticity factor of less than 3 dB over a 4.5% bandwidth. Research [94] presents a simple and accurate methodology for the complete characterization of septum polarizer for 5G applications. The developed technique was applied for the polarizer operating in Ku-band.

Typically, a waveguide polarizer provides good matching for propagating electromagnetic modes of both orthogonal polarizations. The amplitudes of field components with orthogonal linear polarizations at the polarizer's input and output are equal with high accuracy. In fact, any fabricated guide polarizer has imperfect matching. Thus, to calculate the polarization characteristics (ellipticity and ILP at the output) of a polarizer one must take into account the deviations between amplitudes of field vectors with perpendicular linear polarizations at the output port.

The comparison of optimal compact structures of guide polarizers with diaphragms and determination of their sizes for a specified frequency band of satellite systems remains a relevant problem, which is solved in the article. Besides, most part of the research on polarizers base the calculation of all polarization characteristics only on the differential phase shift introduced by the polarizer. Therefore, additional novelty of the presented article consists in the account of difference between the amplitudes of orthogonally polarized field components simultaneously with the output phase difference between them in guide polarizers.

The ellipticity ratio, ILP at the polarizer's output along with the output phase difference, reflection factor and transmission factor for the modes of two perpendicular polarizations will be simultaneously considered for the optimization of polarizers. The goals of optimization are obtaining of reflection factors for waves with perpendicular linear polarizations less than −24 dB and of IPL higher than 30 dB in the operating frequency band 10.7–12.75 GHz.

III. Working mechanism of a guide polarizer and its polarization characteristics

Any polarizer does not provide ideal equality of the amplitudes of orthogonal linearly polarized components at its output in the whole operating frequency band. Besides, the polarizer does not introduce differential phase shift, which is exactly equal to required 90° in the whole operating frequency band. Consequently, accurate theoretical formulas must be applied to estimate the phase and polarization characteristics of a guide polarizer.

In the general case complex amplitudes of electric field vectors of the fundamental electromagnetic modes TE_{10} with perpendicular vertical and horizontal linear polarizations lie in the transversal plane and can be written as follows:

$$\dot{\vec{E}}_{vert} = E_v e^{i\varphi_v}\vec{v}\,; \quad \dot{\vec{E}}_{hor} = E_h e^{i\varphi_h}\vec{h}\,, \tag{1}$$

where E_v and E_h denote the amplitudes of corresponding electric fields directed along the unit vectors $\vec{v}$ and $\vec{h}$ of the perpendicular vertical and horizontal axes, respectively. Symbols φ_v and φ_h stand for the phases of the main electromagnetic waves at the output port of a guide polarization converter.

Now we us introduce the average phase and the phase difference as follows: $\varphi_0 = (\varphi_v + \varphi_h)/2$; $\Delta\varphi = \varphi_h - \varphi_v$.

Then the phases φ_v and φ_h are expressed as follows:

$$\varphi_v = \varphi_0 - \Delta\varphi/2; \quad \varphi_h = \varphi_0 + \Delta\varphi/2. \qquad (2)$$

After this the substitution of (2) into the expressions (1) is carried out. Then the superposition of two orthogonal fundamental modes with perpendicular linear polarizations at the output port of a guide polarizer is as follows:

$$\dot{\vec{E}}_{\text{sup}} = \dot{\vec{E}}_{vert} + \dot{\vec{E}}_{hor} = E_v e^{i(\varphi_0 - \Delta\varphi/2)}\vec{v} + E_h e^{i(\varphi_0+\Delta\varphi/2)}\vec{h} =$$
$$= e^{i\varphi_0}\left(E_v e^{-i\Delta\varphi/2}\vec{v} + E_h e^{i\Delta\varphi/2}\vec{h}\right). \qquad (3)$$

Next, we find components with LHCP and RHCP ($\dot{L}$ and $\dot{R}$) of the total complex amplitude (3):

$$E_v e^{-i\Delta\varphi/2}\vec{v} + E_h e^{i\Delta\varphi/2}\vec{h} = \dot{L}(\vec{e}_v + i\cdot\vec{e}_h) + \dot{R}(\vec{e}_v - i\cdot\vec{e}_h).$$

Now we can separate two linear equations relative to the amplitudes $\dot{L}$, $\dot{R}$ and solve the following system:

$$\begin{cases} \dot{L} + \dot{R} = E_v e^{-i\Delta\varphi/2} \\ \dot{L} - \dot{R} = -iE_h e^{i\Delta\varphi/2} \end{cases}. \qquad (4)$$

To solve this set, it is enough to consequently add and subtract equations (4). The result will be as follows:

$$\begin{cases} 2\dot{L} = E_v e^{-i\Delta\varphi/2} - iE_h e^{i\Delta\varphi/2} \\ 2\dot{R} = E_v e^{-i\Delta\varphi/2} + iE_h e^{i\Delta\varphi/2} \end{cases}. \qquad (5)$$

Let us divide equations of the set (5) by 2 and use Euler formulas to find the complex amplitudes $\dot{L}$ and $\dot{R}$:

$$\dot{L} = \frac{1}{2}\left(E_v\cos\frac{\Delta\varphi}{2} - iE_v\sin\frac{\Delta\varphi}{2} - iE_h\cos\frac{\Delta\varphi}{2} + E_h\sin\frac{\Delta\varphi}{2}\right);$$
$$\dot{R} = \frac{1}{2}\left(E_v\cos\frac{\Delta\varphi}{2} - iE_v\sin\frac{\Delta\varphi}{2} + iE_h\cos\frac{\Delta\varphi}{2} - E_h\sin\frac{\Delta\varphi}{2}\right).$$

Next, we must obtain the modules of the last expressions for complex amplitudes and perform their simplification. These transformations will lead us to the following formulas:

$$L = \frac{1}{2}\sqrt{E_v{}^2 + E_h{}^2 + 2E_vE_h\sin\Delta\varphi}\,; \qquad (6)$$

$$R = \frac{1}{2}\sqrt{E_v{}^2 + E_h{}^2 - 2E_vE_h\sin\Delta\varphi}\,. \qquad (7)$$

Now we will find the ellipticity coefficient for the considered sum of electromagnetic modes with LHCP and RHCP with corresponding complex amplitudes $\dot{L}$ and $\dot{R}$. General complex amplitudes vectors of these two electromagnetic waves are expressed as follows:

$$\dot{\vec{E}}_{\text{LHCP}} = L\cdot e^{i\varphi_L}(\vec{e}_v + i\cdot\vec{e}_h);\ \dot{\vec{E}}_{\text{RHCP}} = R\cdot e^{i\varphi_R}(\vec{e}_v - i\cdot\vec{e}_h). \quad (8)$$

To perform the transformations, we separate the central phase and phase difference between the LHCP and RHCP electromagnetic waves with amplitudes (8) as follows:

$$\varphi_{0\,\text{CP}} = \frac{\varphi_L + \varphi_R}{2}; \quad \Delta\varphi_{\text{CP}} = \varphi_R - \varphi_L.$$

These denotations allow us to rewrite the phases of orthogonal LHCP and RHCP components as follows:

$$\varphi_L = \varphi_{0\,\text{CP}} - \Delta\varphi_{\text{CP}}/2; \quad \varphi_R = \varphi_{0\,\text{CP}} + \Delta\varphi_{\text{CP}}/2. \qquad (9)$$

Having applied the introduced denotations (9), we expand the sum complex amplitudes of two electromagnetic modes with the orthogonal circular polarizations at the output port of a guide polarizer:

$$\dot{\vec{E}}_{\text{sup}} = \dot{\vec{E}}_{\text{LHCP}} + \dot{\vec{E}}_{\text{RHCP}} =$$
$$= L\cdot e^{i\left(\varphi_{0\,\text{CP}} - \frac{\Delta\varphi_{\text{CP}}}{2}\right)}(\vec{e}_v + i\cdot\vec{e}_h) + R\cdot e^{i\left(\varphi_{0\,\text{CP}} + \frac{\Delta\varphi_{\text{CP}}}{2}\right)}(\vec{e}_v - i\cdot\vec{e}_h) =$$
$$= e^{i\varphi_{0\,\text{CP}}}\left[\vec{e}_v\left(L\cdot e^{-i\frac{\Delta\varphi_{\text{CP}}}{2}} + R\cdot e^{i\frac{\Delta\varphi_{\text{CP}}}{2}}\right) + \right.$$
$$\left. + i\cdot\vec{e}_h\left(L\cdot e^{-i\frac{\Delta\varphi_{\text{CP}}}{2}} - R\cdot e^{i\frac{\Delta\varphi_{\text{CP}}}{2}}\right)\right].$$

The utilization of Euler formulas relatively to the last expression leads us to the following formula for the considered sum of complex amplitudes:

$$\dot{\vec{E}}_{\text{sup}} = e^{i\varphi_{0\,\text{CP}}}\left[\vec{e}_v\left(L\cos\frac{\Delta\varphi_{\text{CP}}}{2} - iL\sin\frac{\Delta\varphi_{\text{CP}}}{2} + \right.\right.$$
$$\left. + R\cos\frac{\Delta\varphi_{\text{CP}}}{2} + iR\sin\frac{\Delta\varphi_{\text{CP}}}{2}\right) +$$
$$+ i\vec{e}_h\left(L\cos\frac{\Delta\varphi_{\text{CP}}}{2} - iL\sin\frac{\Delta\varphi_{\text{CP}}}{2} - \right.$$
$$\left.\left. - R\cos\frac{\Delta\varphi_{\text{CP}}}{2} - iR\sin\frac{\Delta\varphi_{\text{CP}}}{2}\right)\right] =$$
$$= e^{i\varphi_{0\,\text{CP}}}\left[\vec{e}_v\left((L+R)\cos\frac{\Delta\varphi_{\text{CP}}}{2} - i(L-R)\sin\frac{\Delta\varphi_{\text{CP}}}{2}\right) + \right.$$
$$\left. + i\vec{e}_h\left((L-R)\cos\frac{\Delta\varphi_{\text{CP}}}{2} - i(L+R)\sin\frac{\Delta\varphi_{\text{CP}}}{2}\right)\right] =$$
$$= e^{i\varphi_{0\,\text{CP}}}\left[(L+R)\left(\vec{e}_v\cos\frac{\Delta\varphi_{\text{CP}}}{2} + \vec{e}_R\sin\frac{\Delta\varphi_{\text{CP}}}{2}\right) - \right.$$
$$\left. - i(L-R)\left(\vec{e}_v\sin\frac{\Delta\varphi_{\text{CP}}}{2} - \vec{e}_R\cos\frac{\Delta\varphi_{\text{CP}}}{2}\right)\right] =$$
$$= e^{i\varphi_{0\,\text{CP}}}\left[(L+R)\vec{e}_1 - i(L-R)\vec{e}_2\right], \qquad (10)$$

where $\vec{e}_1 = \vec{e}_v\cos\frac{\Delta\varphi_{\text{CP}}}{2} + \vec{e}_h\sin\frac{\Delta\varphi_{\text{CP}}}{2}$;

$$\vec{e}_2 = \vec{e}_v\sin\frac{\Delta\varphi_{\text{CP}}}{2} - \vec{e}_h\cos\frac{\Delta\varphi_{\text{CP}}}{2}.$$

Next, we obtain the modules of the vectors $\vec{e}_1$ and $\vec{e}_2$:

$$|\,\vec{e}_1\,| = \sqrt{\left(\cos\frac{\Delta\varphi_{\text{CP}}}{2}\right)^2 + \left(\sin\frac{\Delta\varphi_{\text{CP}}}{2}\right)^2} = 1;$$

$$|\,\vec{e}_2\,| = \sqrt{\left(\sin\frac{\Delta\varphi_{\text{CP}}}{2}\right)^2 + \left(\cos\frac{\Delta\varphi_{\text{CP}}}{2}\right)^2} = 1.$$

Obtained values mean that $\vec{e}_1$ and $\vec{e}_2$ are unit vectors.

Let us calculate scalar product of vectors $\vec{e}_1$ and $\vec{e}_2$:

$$\vec{e}_1 \cdot \vec{e}_2 = \cos\frac{\Delta\varphi_{CP}}{2}\cdot\sin\frac{\Delta\varphi_{CP}}{2} - \sin\frac{\Delta\varphi_{CP}}{2}\cdot\cos\frac{\Delta\varphi_{CP}}{2} = 0\cdot$$

Cosine of the angle between vectors $\vec{e}_1$ and $\vec{e}_2$ is:

$$\cos\left(\vec{e}_1 \hat{;} \vec{e}_2\right) = \frac{\vec{e}_1 \cdot \vec{e}_2}{|\vec{e}_1|\cdot|\vec{e}_2|} = 0,$$

which indicates that the geometrical angle between the considered unit vectors $\vec{e}_1$ and $\vec{e}_2$ is equal to 90°.

Therefore, we make a conclusion that the vectors $\vec{e}_1$ and $\vec{e}_2$ are unit coordinate vectors of the new inclined orthogonal coordinate system. They are parallel to the long a and short b axes of the polarization ellipse of electromagnetic wave at an output port. Thus, the ellipticity coefficient is the ratio between the modules of these axes.

As a result, we obtain ellipticity coefficient p of the polarization ellipse from formula (10) as follows:

$$p = \frac{a}{b} = \left|\frac{L+R}{L-R}\right|. \quad (11)$$

Having substituted expressions (6) and (7) into the square of the formula (11), we obtain the following formula for the squared axial ratio of electromagnetic wave at the output port of a guide polarizer:

$$p^2 = \frac{E_v^2 + E_h^2 + \sqrt{E_v^4 + E_h^4 + 2E_v^2E_h^2\cos(2\Delta\varphi)}}{E_v^2 + E_h^2 - \sqrt{E_v^4 + E_h^4 + 2E_v^2E_h^2\cos(2\Delta\varphi)}}. \quad (12)$$

Another frequently applied value to characterize the polarization state of electromagnetic wave in guide polarizers, which is directly connected with the ellipticity coefficient, is isolation of linear polarizations. In the considered circular polarization basis it is equal to the ratio of the modules of LHCP and RHCP components. According to definition we obtain the following expression:

$$\mathrm{ILP} = \frac{L}{R} = \frac{\sqrt{E_v^2 + E_h^2 + 2E_vE_h\sin\Delta\varphi}}{\sqrt{E_v^2 + E_h^2 - 2E_vE_h\sin\Delta\varphi}}. \quad (13)$$

If a polarizer introduces phase shift $\Delta\varphi = 90°$ and the input electromagnetic mode with linear polarization has perpendicular in-phase components with equal amplitudes (i.e. the mode enters a polarizer with 45° inclination angle), then $E_v = E_h$. Substitution of these values into (12) and (13) leads to the ellipticity coefficient $p = \pm 1$ and ILP $\rightarrow \infty$, which obviously indicates a circularly polarized electromagnetic wave at the output port of a polarizer.

IV. Diaphragm polarizer designs and their performance

This section presents the results of comparative analysis of electromagnetic characteristics of compact polarization converters based on a square guide with different number of diaphragms in a design (from 3 to 5).

For computer modeling of considered characteristics we will apply finite elements method in the frequency domain. In [95–97] the authors have shown that mentioned method provides better convergence of the characteristics than FDTD method. Besides, the calculation time of finite elements method in frequency domain is twice less than that time of FDTD method.

A. SQUARE GUIDE POLARIZER WITH THREE DIAPHRAGMS

A three-dimensional inner view of a square guide polarizer with 3 diaphragms is shown in Fig. 1. In addition, all inner sizes of a structure are also presented in the figure. Denoted dimensions have been varying in the process of optimization of the square guide polarizer to bring its electromagnetic characteristics to the required values. The process of numerical optimization of presented microwave device involves changing of its dimensions in order to obtain the best characteristics in the operating frequency range. The diaphragms can be manufactured as integrated into a polarizer structure by milling of a single metal brick.

The middle diaphragm has a height of h_2. It is higher than the other two diaphragms of the same height h_1 to ensure better matching. The distance between diaphragms is L_1. All diaphragms have the same thickness w.

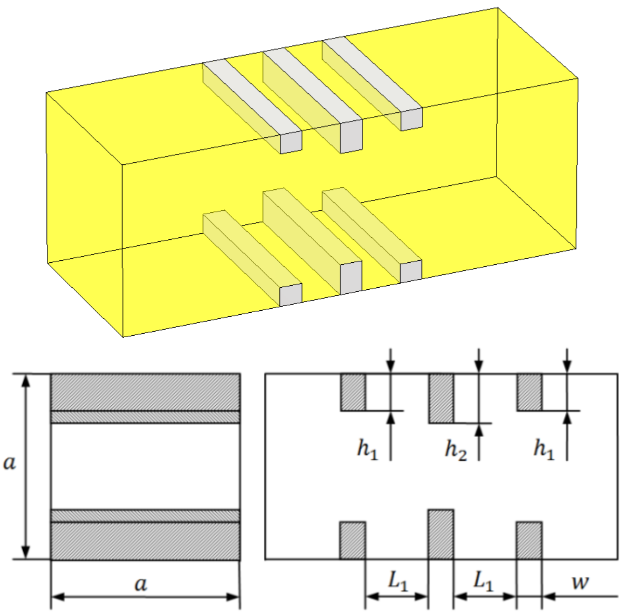


FIGURE 1. 3-D model of a square guide polarizer with three diaphragms

Fig. 2 demonstrates main electromagnetic parameters of the compact square guide polarizer with three diaphragms in the operating Ku-band 10.7–12.75 GHz.

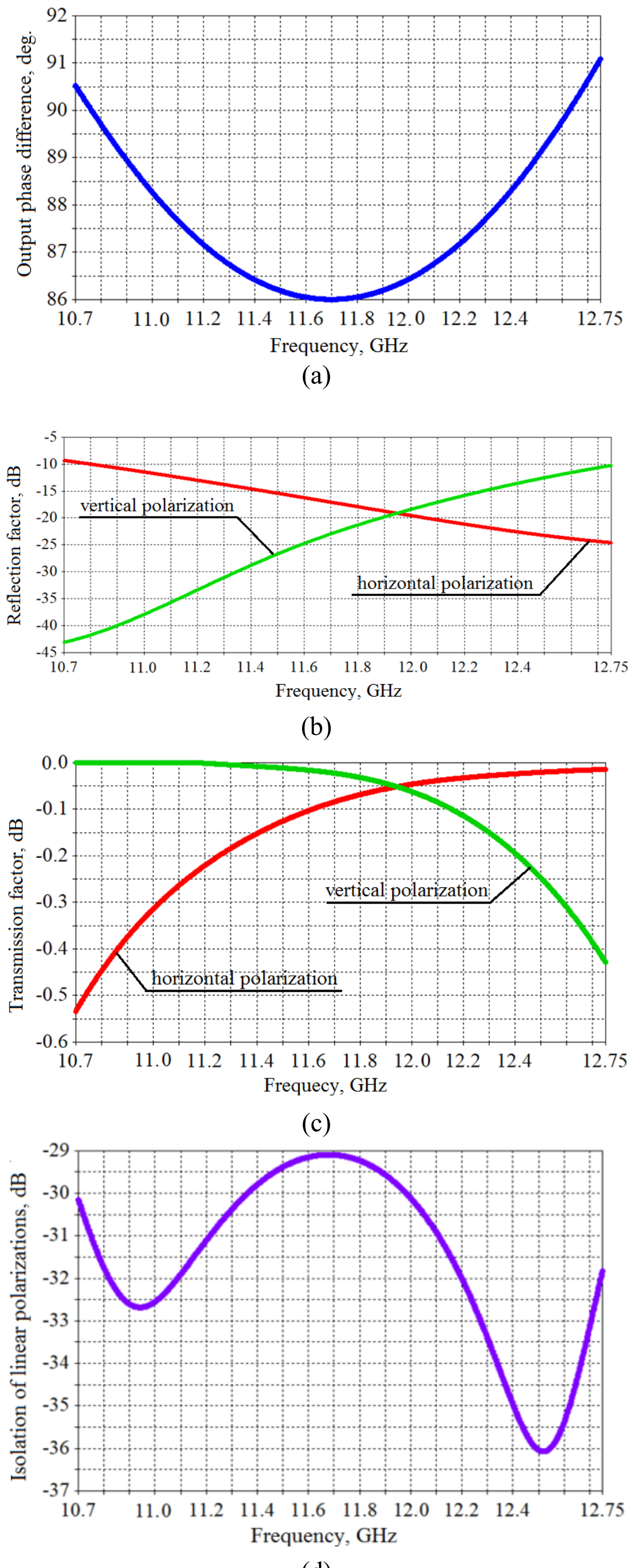


FIGURE 2. Main electromagnetic parameters of a a square guide polarizer with three diaphragms, (a) output phase difference, (b) reflection factor, (c) transmission factor, (d) isolation of linear polarization

Fig. 2a presents the function of output phase difference on frequency in Ku-band 10.7–12.75 GHz. As one can observe, the output phase difference is equal to 90° at the frequencies of 10.76 GHz and 12.63 GHz. In the operating frequency interval 10.7–12.75 GHz the output phase difference changes from 86° to 91°. It is seen in Fig. 2a that at 11.7 GHz the highest deviation of the output phase difference from 90° is equal to 4°.

Fig. 2b shows the functions of reflection factor on frequency for both linear perpendicular polarizations in the frequency interval 10.7–12.75 GHz. It is seen that the highest value of reflection factor for both polarizations for the guide polarizer with three diaphragms is −9.0 dB and it is achieved at the minimum frequency 10.7 GHz. Fig. 2c presents transmission factors for both linear polarizations in the frequency interval 10.7–12.75 GHz. It is seen that the minimal value of transmission factor for both polarizations is −0.54 dB and it occurs at the minimum frequency 10.7 GHz. The function of ILP in the frequency interval 10.7–12.75 GHz is presented in Fig. 2d. As one can indicate in Fig. 2d, the ILP of this guide polarizer is higher than −29 dB. The lowest ILP appears at the frequency of 11.7 GHz, which agrees with the frequency of the highest deviation of output phase difference of the optimized device from 90°. Moreover, two minimum values of ILP can be observed at the frequencies of 10.93 GHz and 12.51 GHz, which does not exactly coincide with the frequencies at which the output phase difference is 90°. This discrepancy is explained by a significant influence of the frequency characteristics of reflection and transmission factors, which differ for vertical and horizontal linear polarizations.

Therefore, by applying three or more diaphragms in the construction of a guide polarizer one can get the output phase difference, which is quite close to 90° in frequency interval 10.7–12.75 GHz, but the corresponding ILP does not reach the required level of 30 dB. Besides, there remains bad matching of the developed guide polarizer with 3 diaphragms. The reason of this is a small number of diaphragms in the construction, which cannot compensate for reflections of electromagnetic waves at them. Consequently, to obtain required matching of the developed guide polarizer it is necessary to increment the number of applied diaphragms

B. SQUARE GUIDE POLARIZER WITH FOUR DIAPHRAGMS

A three-dimensional model and all sizes of a square waveguide polarizer with four diaphragms is shown in Fig. 1. The middle diaphragms have a height of h_2. They are higher than the other two diaphragms of the same height h_1 to ensure better matching. The distance between the central diaphragms is L_2, the distance between the central and external diaphragms is L_2. All diaphragms have the same thickness w.

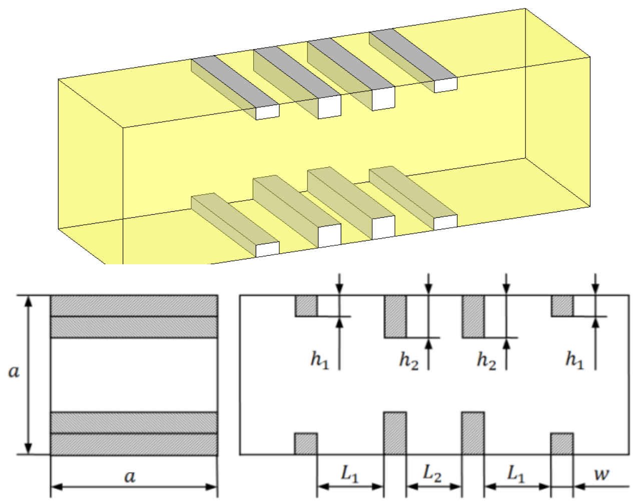
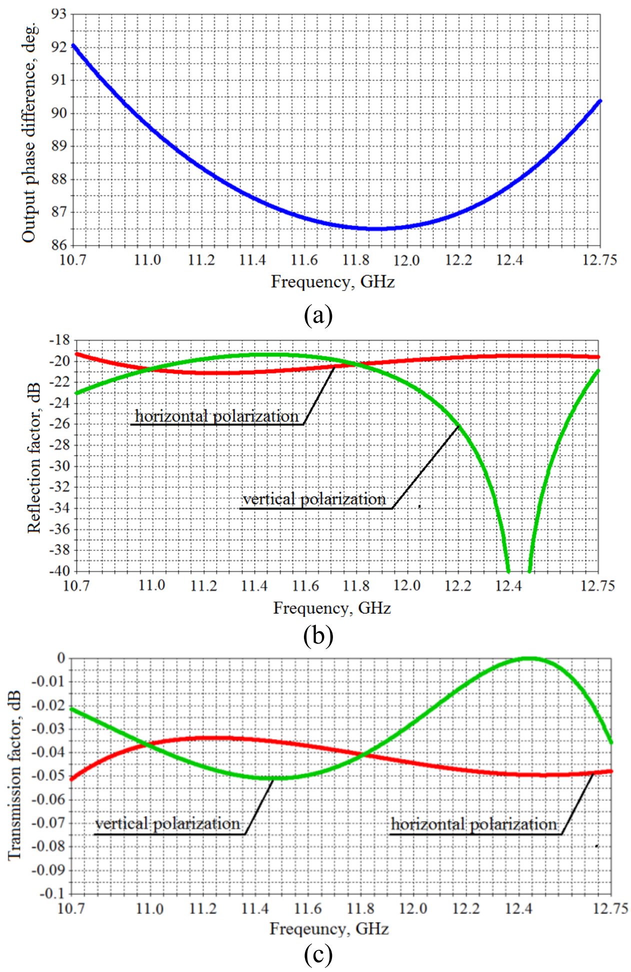


FIGURE 3.3-D model of a square guide polarizer with three diaphragms

Fig. 2 illustrates main parameters of the optimized compact square guide polarizer with four diaphragms in the operating Ku-band 10.7–12.75 GHz.



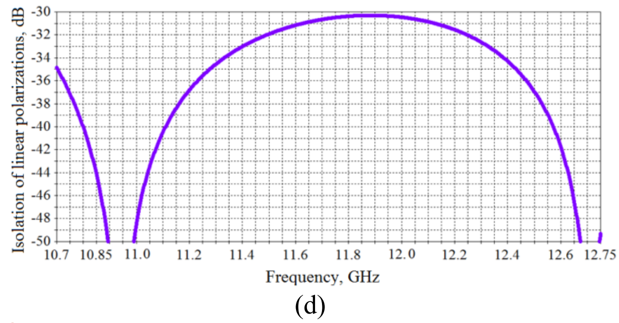


FIGURE 4. Main electromagnetic parameters of a a square guide polarizer with four diaphragms, (a) output phase difference, (b) reflection factor, (c) transmission factor, (d) isolation of linear polarization

Fig. 2a illustrates the output phase difference of the developed microwave device with four diaphragms. As one can observe, the output phase difference of a device is equal to 90° at the frequencies 10.94 GHz and 12.71 GHz. In the frequency interval 10.7–12.8 GHz the output phase difference changes from 86.5° to 92.1°. At the frequency of 11.9 GHz there occurs the largest difference of the output phase difference from 90°, which is equal to 3.5°.

The functions of reflection factor on frequency for linear polarizations in the operating band 10.7–12.8 GHz are shown in Fig 6b. As one can see, the peak level of reflection factors for both polarizations is −19 dB. Fig. 2c presents transmission factor for both polarizations in the frequency interval 10.7–12.75 GHz. It is worth nothing that the minimal value of reflection factor for both polarizations is −0.05 dB and it is reached at the frequencies of 10.7 GHz and 12.43 GHz. The function of ILP on frequency in the operating band 10.7–12.75 GHz is indicated in Fig. 2 d. It is observed that the peak ILP level is 30.3 dB. It is seen that the lowest ILP and the maximum difference of output phase difference of a polarizer from 90º are reached at the frequency of 11.9 GHz. In addition, two minimum values of IPL are observed at the frequencies 10.94 and 12.71 GHz, at which the output phase difference is 90°.

Hence, in the frequency interval 10.7–12.75 GHz the designed polarizer with four diaphragms has the following parameters: the output phase difference is in the range 90° ± 3.5°, reflection factor of both perpendicular linear polarizations is less than −19 dB, the transmission factor is greater than −0.05 dB, the ILP is better than 30.3 dB. Therefore, the proposed guide polarizer with four diaphragms maintains required polarization purity parameters, but it demands further improvement of its matching.

C. SQUARE GUIDE POLARIZER WITH FIVE DIAPHRAGMS

A three-dimensional model of the analyzed square guide polarizer with five diaphragms is shown in Fig. 1. The construction of this microwave device is such as the ones examined hereinbefore. An additional diaphragm has been added in the middle. The length of central diaphragm h_3 is the highest, the lengths of two lower middle diaphragms are

h_2 and the lengths of two outside diaphragms h_1 are the shortest ones. All used diaphragms have the same thickness w. The distances between the central and middle diaphragms are designated as L_1 and the distance between the outside and middle ones are denoted as L_2.

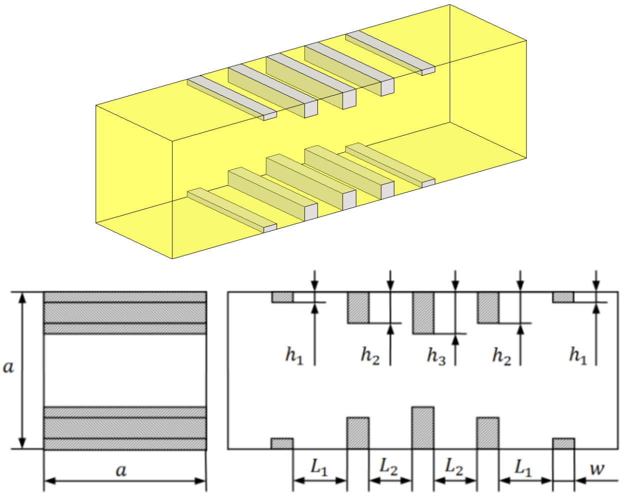
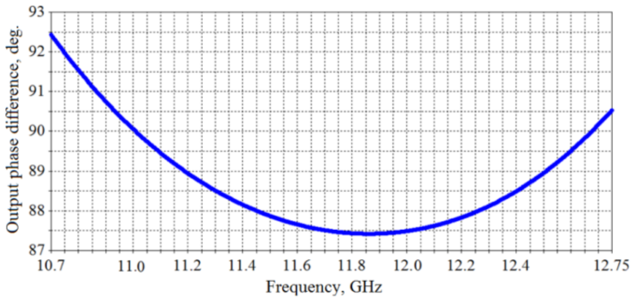
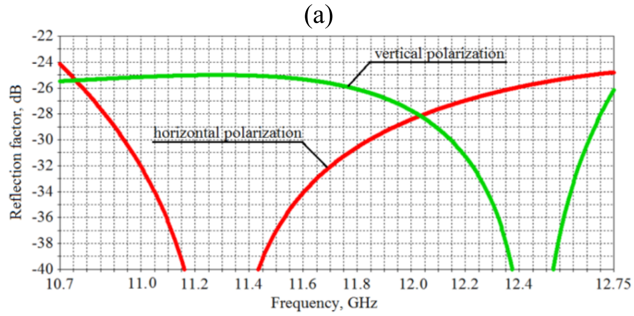


FIGURE 5.3-D model of a square guide polarizer with five diaphragms

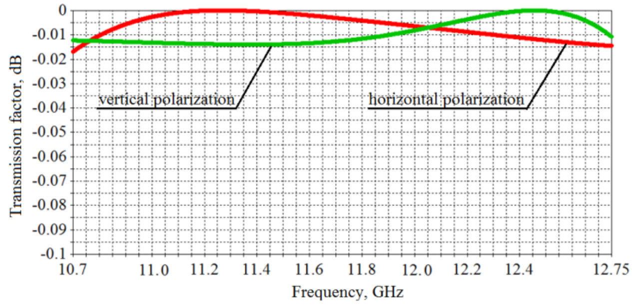
Fig. 2 demonstrates main electromagnetic parameters of the developed guide polarizer with five diaphragms in the frequency interval 10.7–12.75 GHz.



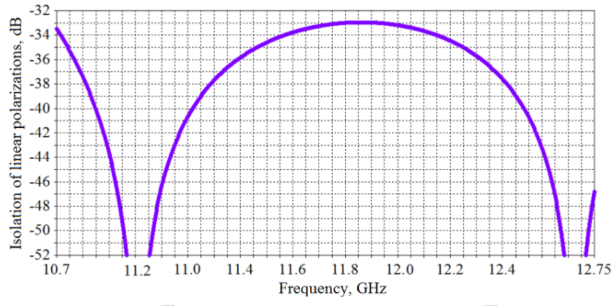
(a)



(b)



(c)



(d)

FIGURE 6. Main electromagnetic parameters of a a square guide polarizer with five diaphragms, (a) output phase difference, (b) reflection factor, (c) transmission factor, (d) isolation of linear polarization

Fig. 2a depicts the dependence of output phase difference on frequency. As one can observe, the output phase difference of the device is equal to 90° at the frequencies 11.0 GHz and 12.67 GHz. Within the frequency interval 10.7–12.75 GHz the output phase difference of the polarizer alters from 87.4° to 92.4°. Therefore, the output phase difference is 90°±2.6°. This change is minimum among all output phase differences of the considered guide polarizers.

The functions of reflection factors on frequency for both perpendicular linear polarizations are shown in Fig. 2 b. It is seen that in the operating band 10.7–12.75 GHz the highest level of reflection factor is −24 dB and it is reached at the frequency 10.7 GHz. In Fig. 2b it is seen that the dependences of reflection factors of the developed polarizer with five diaphragms on frequency are not monotonic functions in contrast to the ones obtained for the transducer of polarizations with two and three diaphragms. For main modes of vertical and horizontal linear polarizations the dependences of reflection factor on frequency have a single lowest value in the frequency interval 10.7–12.75 GHz, which indicates the perfect matching of the device. Fig. 2c presents transmission factors for both polarizations in the frequency interval 10.7–12.75 GHz. It is worth nothing that the minimal value of reflection factor for both polarizations is −0.017 dB and it is achieved at the frequency 10.7 GHz. The frequency dependence of ILP of the presented polarizer is plotted in Fig. 2 d. It is seen that in the operating frequency band the ILP of the device is higher than 32.9 dB. It should be noted that the worst ILP can be seen at the frequency 11.87 GHz, which coincides to the frequency of highest change of output phase difference of the device from 90°. Two minima of the ILP dependence correspond to frequencies of 11.0 GHz and 12.68 GHz, which coincide with the frequencies where the output phase difference is equal to the value of 90°.

Consequently, in the frequency band 10.7–12.75 GHz the developed square guide polarizer with five diaphragms provides the electromagnetic parameters as follows: the output phase difference is 90° ± 2.6°, the reflection factors for both perpendicular linear polarizations are lower than −24 dB, the transmission factors are higher than −0.017 dB, the ILP is higher than −32.9 dB. Therefore, the application of five diaphragms has allowed to obtain a guide polarizer design, which simultaneously satisfies the requirements to polarization purity and matching.

V. Comparison of obtained results and discussion

All designed compact polarization converters can be simply fabricated applying milling technology. Let us compare the sizes and electromagnetic parameters of the presented microwave devices depending on the number of applied diaphragms.

Table I demonstrates all inner sizes of the guide polarizer converters, which were designed for the operating frequency interval 10.7–12.75 GHz. As one can see in Table 1, the increment of number of diaphragms results in the decrement of the size *a* of square guide walls, which improves the compactness of a guide polarizer in transversal directions.

Table II compares electromagnetic characteristics of the developed guide polarizers with number of diaphragms from 3 to 5 in the frequency interval 10.7–12.75 GHz.

TABLE I. DIMENSIONS OF THE SQUARE GUIDE POLARIZERS WITH DIAPHRAGMS

Number of diaphragms	*three*	*four*	*five*
Size of square guide walls (a), mm	21.98	21.61	21.49
Height of the lowest diaphragms (h_1), mm	2.45	1.77	0.99
Height of the medium diaphragms (h_2),	3.86	2.99	2.64
Height of the highest diaphragms (h_3), mm	—	—	3.06
Gap between the outer diaphragms (L_1), mm	4.92	5.86	6.06
Gap between the inner diaphragms (L_2), mm	—	4.68	5.48
Thickness of all diaphragms (*w*), mm	2.79	3.44	2.88

TABLE II. ELECTROMAGNETIC PARAMETERS OF POLARIZERS WITH DIAPHRAGMS

Number of diaphragms	*three*	*four*	*five*
Output phase difference	90° ± 4.0°	90° ± 3.5°	90° ± 2.6°
Maximum reflection factor, dB	-9	-23	-24
Minimum transmission factor, dB	-0.53	-0.05	-0.017
Minimum ILP, dB	29.0	30.3	32.9

The increment of a number of diaphragms applied in the construction leads to the decrease of the output phase difference introduced by each diaphragm, because the total output phase difference at the device's output is close to 90° in each case. This results in the decrement of heights of the diaphragms as their amount becomes greater, which is seen in Table 1. As it was expected, the decrement of the diaphragm heights results in the improvement of matching of the polarizer's structure, which is confirmed by Table 2.

It is seen in the Table I that the increment of amount of the diaphragms leads to the increment of the gaps between them. This phenomenon can be explained based on the physics of the electromagnetic waves propagation in the microwave device. The increment of number of the diaphragms results in more low heights. Accordingly, each diaphragm would concentrate the electric field and its energy less intensively. Then matching of the polarizer's design is provided by the similar discontinuities, which would be placed at longer distances. The opposite physical phenomenon is observed in the matching resonators of ultrawideband quad-ridged antennas and orthomode transducers [26, 51], which are shorter than the quarter-wavelength resonators.

As one can see in the Table I, the thickness of diaphragms of compact square guide polarizers in frequency interval 10.7–12.75 GHz falls in the range 2.8–3.4 mm and it weakly depends on the amount of diaphragms. The relative thickness of diaphragms is (0.11–0.13)·λ_0, where λ_0 stands for the length of wave at the centre frequency 11.75 GHz.

We see that in all optimized polarizer designs the height of the middle diaphragm and the gap between diaphragms weakly depend on the amount of diaphragms. Table 1 demonstrates that they fall in the ranges 2.99–3.86 mm (which is (0.12–0.15)·λ_0) and 4.92–6.06 mm (which is (0.19–0.24)·λ_0), respectively. Hence, in all designed constructions of polarizers the height of the middle diaphragm is approximately equal to the diaphragm thickness, and the gap between diaphragms is 1.4–2.1 times greater than their thickness.

It is seen in the Table II that the guide polarizers with 3 and 4 diaphragms do not ensure required in most feed systems matching, because the maximum level of reflection factor is much greater than −24 dB. Besides, it can be seen from Table 2 that the minimum ILP level of the polarization converters with 3 and 4 diaphragms is less than 32 dB. Accordingly, to provide simultaneously good matching and polarization electromagnetic characteristics in the operating frequency band 10.7–12.75 GHz five or more diaphragms must be applied in the construction of polarization converter based on square guide with the conducting diaphragms.

VI. CONCLUSIONS

In this article we developed compact guide polarizers with diaphragms and carried out their comparative analysis. A comparison was made for the electromagnetic characteristics and inner dimensions of square guide polarizers with different number of diaphragms from 3 to 5.

In the operating frequency band 10.7–12.75 GHz the square guide polarizer with five diaphragms ensured excellent performance with the following characteristics: the reflection factor is less than −24 dB and the transmission factor is greater than −0.017 dB for both perpendicular linear polarizations, the output phase difference is 90° ± 2.6°, the isolation of linear polarizations is less than −32.9 dB.

Consequently, the designed square guide polarization converter with five diaphragms has effective performance combined with a compact design. Obtained in this research results can be applied for the development of new guide polarizers for satellite communication systems and radars.

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