Visnyk NTUU KPI Seriia – Radiotekhnika Radioaparatobuduvannia, 2020, Iss. 83, pp. 17–28

УДК 621.396

Equivalent Microwave Circuit Technique for Waveguide Iris Polarizers Development

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The increase of information volumes, which are transmitted in modern satellite telecommunication systems, requires the development of new signal processing technologies, microwave devices, antenna systems and methods of their analysis. In particular, polarization-adaptive antennas are widely used for this purpose. Such antennas provide the possibility to transmit and receive radio signals with polarization of any type. Polarization processing devices of antenna systems must provide low levels of voltage standing wave ratio of waves with horizontal and vertical linear polarizations and high crosspolar discrimination simultaneously. Therefore, there is the need to improve designs and methods of analysis of modern polarization processing devices. Polarizers based on a square waveguides with irises are widely used due to the simplicity of their design and manufacturing by milling technology. The article considers a new mathematical model of waveguide polarizers with reactive irises. For the example of model application we have simulated and optimized a polarizer based on a square waveguide with four irises. A mathematical model of this waveguide polarizer was developed based on the description of microwave devices and their elements by wave scattering and transmission matrices. The general scattering matrix of the polarizer has been obtained analytically. The main electromagnetic characteristics of the polarizer were determined based on the elements of this matrix. As a result, we have analyzed main characteristics of the model, including differential phase shift, voltage standing wave ratio for vertical and horizontal polarizations, axial ratio and crosspolar discrimination. The optimization of the characteristics of a polarizer has been performed using the developed mathematical model and a software based on the finite integration technique. The optimal characteristics and geometrical sizes of the structure are in good agreement, which proves the correctness of the developed mathematical model of square waveguide iris polarizers.

Key words: polarizer; waveguide polarizer; iris polarizer; circular polarization; scattering matrix; transmission matrix; differential phase shift; voltage standing wave ratio; axial ratio; crosspolar discrimination

DOI: 10.20535/RADAP.2020.83.17-28

Introduction

Nowadays a progressive area of modern telecommunication technologies is adaptive antenna systems with signal polarization processing. Application of polarization processing increases the efficiency of telecommunication and radar systems for various purposes. The key elements of such systems are devices for transformation of polarization type and separation of signals with orthogonal polarizations to different channels.

A large number of scientific papers are dedicated to numerical simulation and analysis of microwave devices of signal polarization processing [1–7]. For development of new waveguide polarizers and optimization of their characteristics it is necessary to calculate them with high accuracy. Therefore, it is important engineering problem to create new analytical techniques and mathematical models for simulation of waveguide polarizers and improvement of their performance. In this research we develop a simple mathematical method for the analysis of polarizers based on reactive elements in a waveguide. The obtained model is effectively applied for the optimization of new waveguide iris polarizer for C-band 3.4–4.2 GHz.

1 Analysis of modern researches on waveguide polarizers

Modern microwave devices for signal polarization processing are created based on the waveguides with posts, ridged structures, corrugations and irises. The application of ridges in the design allows to create ultrawideband waveguide polarizers [8, 9]. Modern investigations of ridged structures and structures with irises are carried out using various mathematical methods. Among such methods there are mode matching technique [10], transverse field-matching technique [11–14], magnetic field integral equation technique

[15, 16], and integral equations technique [17–20] with the account of singularity of the fieldsat the conducting edges, which excludes the relativity of the convergence of series in the transverse field matching technique [21].

One of the main disadvantages of all known numerical techniques based on rigorous mathematical models of polarizers is their great complexity. Therefore, in our research the main emphasis of the investigation is on the use of simpler methods of creating mathematical models based on matrix methods. Such approaches require the application of scattering and transmission wave matrices to describe the characteristics of the waveguide iris polarizer.

The best wideband characteristics are reached in polarizers based on waveguides with irises [1, 22]. A significant number of researches on matrix methods is used to calculate phase shifters based on reactive elements in the waveguide [22–24] and various microwave filters. In [25] the procedure of designing microwave filters is given, which is based on the representation of the filter in the form of a model of a circuit with distributed parameters. This method takes into account multimode interaction and does not use the numerical optimization process. The article [26] is devoted to the general approach to mathematical methods of filter calculation using the method of analytical gradient optimization. Nevertheless, a large number of scientific publications on waveguide polarizers contain only the results of simulations, the process of which takes a large amount of time [27–45].

The article [28] presents a rigorous theoretical and experimental comparison of two kinds of rectangular waveguide polarisers for use in Ka-band gyro-travelling wave amplifier. It is shown by the author how overall field distribution inside of waveguide polariser structures having different kinds of corrugation affects the resulting performances.

In [29] the authors developed and manufactured a new compact septum polarizer operating in the frequency range from 18.5 GHz to 21.5 GHz. The polarizer has an integrated transition from a square to a narrower circular waveguide. The simulated and measured parameters provide an axial ratio less than 0.6 dB. The polarization discrimination is less than 25 dB in the frequency range 18.5–21.5 GHz.

The article [32] introduces parallel-plate ridge gap waveguide consisting of a metal ridge in a metamaterial surface, which is covered by a metallic plate at a small height above it. The metamaterial surface is designed to provide a frequency band where normal global parallel-plate modes are cutoff, thereby allowing a confined gap wave to propagate along the ridge.

In article [33, 34] the authors developed and optimized a new broadband coaxial polarizer for the operating frequency band from 3.4 GHz to 4.8 GHz. In the whole operating frequency band the polarizer [33] provides a differential phase shift of $90° \pm 2.5°$ and the reflection coefficient less than −33 dB. The application of a coaxial waveguide in the structure of a polarizer allows to use it in dual-band antenna feed systems with orthogonal circular polarizations. The antenna feed system includes an iris polarizer for reflector antennas of terrestrial stations with double circular polarizations operating in the extended C-band 3.4–4.8 GHz [34]. The VSWR of the polarizer is 1.14, its crosspolar isolation exceeds 30 dB. The polarizer of the system provides a differential phase shift of $90° \pm 2.8°$.

In [35] the authors developed a broadband compact three-dimensional printed polarizer for the operating frequency band 28–34 GHz. The design consists of a pair of radially opposite grooves inside a circular waveguide and excited using a coaxial probe. This makes the developed design simple and highly compact as compared to the other conventional circular polarizers. The polarizer provides an axial ratio less than 3.0 dB.

The article [36] investigates septum polarizers performance for various fractional bandwidths. In [36] the authors developed and optimized Q- and K-band waveguide polarizers with longitudinal septums of constant thicknesses. The optimal designs and their electromagnetic performance were analyzed for fractional bandwidths from 5% to 20% using finite elements method in the frequency domain.

The authors of [37] developed a broadband septum polarizer with relative bandwidth of 37.8%. This wide operating frequency band is provided by the application of an equilateral triangular waveguide. This waveguide ensures the maximum possible frequency range between the fundamental and first higher modes. Developed polarizer provides an axial ratio less than 1.0 dB.

In the article [38] a new cylindrical horn antenna with left circular polarization for the W-band from 79.5 GHz to 88 GHz was suggested. The developed antenna's feature is the application of an inbuilt polarizer structure and a single side-fed linear polarized input to offer symmetric LHCP radiation pattern. The antenna provides axial ratio less than 1.2 dB and the reflection coefficient less than −15 dB.

The wideband coaxial OMT for the extended operating C-band 3.4–5.4 GHz has been developed in [30, 39]. It provides the coherent reception of orthogonal linearly polarized electromagnetic waves in the whole operation frequency band. The reflection coefficient of the design is less than −27 dB.

In [40, 41] the authors suggested a new waveguide polarizer for operating Ku-band 10.7–12.8 GHz. The electromagnetic characteristics of the developed waveguide polarizer were simulated and optimized using finite integration technique. The polarizer provides VSWR less than 1.24. The axial ratio is less than 0.53 dB. The XPD of the polarizer is higher than 30.3 dB.

The study [42] presented a horn antenna based on a circular waveguide with circular polarization in the range from 54 GHz to 60 GHz. An integral part of the antenna is a polarizer with mono-grooves, which are located at an angle of 45° relative to both input ports. This design creates right and left hand circular polarizations. The system provides an axial ratio of less than 2.2 dB. Polarization isolation is higher than 25 dB. The isolation between the ports is 15 dB

The papers [43, 44] present the results of development of a X-band compact stepped-thickness septum polarizer in the operating frequency band 7.70–8.50 GHz for a quasi-monopulse feed of a dual-polarized ground station antenna system. VSWR of the designed polarizer is less than 1.4. XPD of the polarizer is higher than 30 dB. The measured differential phase shift varies from 83° to 100°.

The new method to design a compact tunable polarization plane rotator in a circular waveguide for X-band was demonstrated by numerical simulations and an experiment in [45]. Being relatively narrowband, the polarizer operates on the eigenoscillations excited inside a pair of conjugated planarchiral irises, which provide different polarization planes on both sides of the unit. Longitudinal dimensions of such a rotator can be less than $\lambda 0/30$. In [46] it was demonstrated that in a two-layer symmetric waveguide the operating frequency band of the polarizer can be expanded.

In [47] the authors proposed a new waveguide polarizer for operating Ku-band 10.7–12.8 GHz. The electromagnetic characteristics of the waveguide polarizer were simulated and optimized using finite integration technique. The polarizer provides VSWR less than 1.13. The axial ratio is less than 0.4 dB. XPD of the developed polarizer is higher than 33 dB. The differential phase shift varies from 87.4° to 92.6°.

Research [48] presents a compact notched-septum polarizer in the form of an integral substrate. The slots close to the notches are used to increase the polarization frequency. Axial ratio is less than 3 dB in 4.5/

In paper [49] the authors suggested a new waveguide iris polarizer for operating X-band 7.4–8.5 GHz. The electromagnetic characteristics of the waveguide polarizer were simulated and optimized using finite integration technique. The polarizer provides VSWR less than 2.8. The axial ratio is less than 1.6 dB, the XPD is higher than 21.7 dB. The differential phase shift of a polarizer varies from 82° to 98°.

In [50] the mathematical model of a waveguide polarizer with irises was created, taking into account the thickness of the irises. A new analytical model of a polarizer has been developed using the equivalent substitution circuits. The main electromagnetic characteristics of the model were determined through the elements of the scattering matrix of a polarizer. The characteristics of a waveguide iris polarizer were optimized in the Ku-band

The authors of an article [51] proposed a compact waveguide polarization rotator capable to rotate the polarization plane by an arbitrary angle. Its operational principle is based on a strong electromagnetic coupling between two conjugated quadruple-slot planar-chiral irises in a square waveguide by the below cutoff modes.

A compact integrated silicon and graphene polarizers are proposed in [52, 53]. The developed polarizer [52] has low insertion loss for TM mode of 0.7 dB and high attenuation for TE mode of 41.25 dB. The configurable waveguide polarizer [53] has highest exting extinction ratio for TM mode of 46 dB and highest extinction ratio for TE mode of 34.9 dB. The variation in the polarization extinction ratio is less than 3.0 dB.

2 Formulation of the research problems

The purpose of current research is to develop a new simple analytical technique for the calculation of all electromagnetic characteristics of square waveguide iris polarizers. The results obtained by the analytical technique must be in good agreement with the ones obtained by other numerical techniques. Another problem, which is solved in the article, is the optimization of the characteristics of a square waveguide polarizer with 4 irises for the operation in C-band 3.4–4.2 GHz.

A waveguide polarizer in the receiving antenna system generates signals with orthogonal linear polarizations at the output. To simplify the analysis in this article we will consider the characteristics of the polarizer in the transmitting antenna. In this case the signals with orthogonal circular polarizations are generated at the output of the polarizer. The development and optimization of the waveguide polarizer is carried out in order to ensure effective polarization and matching characteristics. In particular, the differential phase shift within the range $90° \pm 4°$ is required. VSWR for both polarizations must be less than 1.4. The axial ratio is required to be less than 0.6 dB. The XPD higher than 30 dB is required in the developed polarizer.

3 Theoretical analysis of a square waveguide polarizer with four irises

To eliminate the additional phase distortions of the signals with vertical and horizontal polarizations in the waveguide outside the irises region we choose a waveguide with square cross-section.

The developed model uses thin irises in contrast to the model [50], which uses thick irises. In addition, various analytical calculation methods are used to determine the reactive conductivities of the irises and various equivalent substitution circuits.

The inner structure of the polarizer based on a square waveguide with four irises and the designation of the dimensions of the structure is shown in Fig. 1. In Fig. 1 we see that the two outer irises have the same height h_1 and the two middle irises also have the same height h_2, and the height h_2 is greater than the height h_1 to better matching of the structure. The distance between the inner irises is l_2, and the distance between the outer and inner irises is l_1.

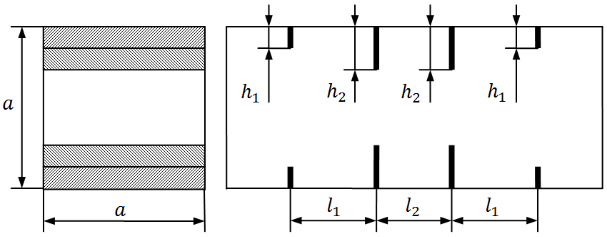

Fig. 1. Inner structure of a waveguide polarizer with four irises

As a result, a mathematical model was developed for the considered waveguide polarizer with four irises by analyzing microwave circuits based on wave matrices of scattering and transmission [54], which contains inductive and capacitive reactive elements.

In Fig. 2 shows a general view of the circuit of a waveguide with four reactive elements based on a single-wave approximation.

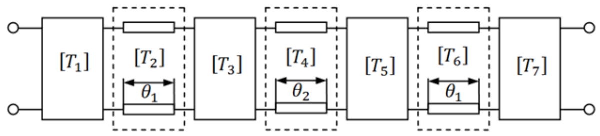

Fig. 2. Equivalent circuit of a waveguide with four irises

Each two-port circuit is described by a wave matrix of transmission [55]

$$
\begin{aligned}
[T_1] = [T_7] &= \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix}; \\
[T_3] = [T_5] &= \begin{bmatrix} T'_{11} & T'_{12} \\ T'_{21} & T'_{22} \end{bmatrix}; \\
[T_2] = [T_6] &= \begin{bmatrix} e^{j\theta_1} & 0 \\ 0 & e^{-j\theta_1} \end{bmatrix}; \\
[T_4] &= \begin{bmatrix} e^{j\theta_2} & 0 \\ 0 & e^{-j\theta_2} \end{bmatrix},
\end{aligned} \tag{1}
$$

where θ_1 and θ_2 are electric lengths of the transmission line expressed in radians.

The electrical length is determined

$$\theta = \frac{2\pi \cdot l}{\lambda_g}, \tag{2}$$

where l is the length between irises expressed in millimeters; λ_g is the guide wavelength expressed in millimeters.

The wavelength in the waveguide is described by the expression

$$\lambda_g = \frac{\lambda_0}{\sqrt{1 - \left(\frac{\lambda_0}{\lambda_C}\right)^2}}, \tag{3}$$

where $\lambda_0 = c/f$ is the wavelength in free space expressed in millimeters, $\lambda_C = 2a$ is cutoff wavelength expressed in millimeters for the TE_{10} mode in the waveguide, a is the length of the wall of a square waveguide expressed in millimeters.

As a result, the transmission matrix is determined

$$
\begin{aligned}
[T_{\sum}] &= \\
&[T_1] \cdot [T_2] \cdot [T_3] \cdot [T_4] \cdot [T_5] \cdot [T_6] \cdot [T_7] = \\
&= \begin{bmatrix} T_{\sum 11} & T_{\sum 12} \\ T_{\sum 21} & T_{\sum 22} \end{bmatrix}.
\end{aligned} \tag{4}
$$

The relationship between transmission and scattering matrices is as follows

$$
\begin{aligned}
[S_{\sum}] &= \begin{bmatrix} S_{\sum 11} & S_{\sum 12} \\ S_{\sum 21} & S_{\sum 22} \end{bmatrix} = \\
&= \frac{1}{T_{\sum 11}} \begin{bmatrix} T_{\sum 21} & |T| \\ 1 & -T_{\sum 12} \end{bmatrix},
\end{aligned} \tag{5}
$$

where $|T|$ is determinant of a matrix $[T_{\sum}]$ from expression (2).

As a result, we have elements of the scattering matrix

$$S_{\sum 21} = \frac{1}{\mathrm{T}_{\sum 11}}; \quad S_{\sum 11} = \frac{\mathrm{T}_{\sum 21}}{\mathrm{T}_{\sum 11}}. \tag{6}$$

To compensate the total reflection from all discontinuities it is necessary to use reactive elements with the same conductivities (irises with equal windows) pairwise. Besides, the distance between the irises must be approximately equal to quarter-wavelength in the waveguide at the central frequency of the operating band.

For a waveform model with inductive (Fig. 3) and capacitive (Fig. 4) irises, the elements of the scattering matrix will be as follows

$$
\begin{aligned}
S_{11L} &= \frac{jb_L}{2 - jb_L}, \quad S_{21L} = \frac{2}{2 - jb_L}, \\
S_{11C} &= \frac{-jb_C}{2 + jb_C}, \quad S_{21C} = \frac{2}{2 + jb_C}.
\end{aligned} \tag{7}
$$

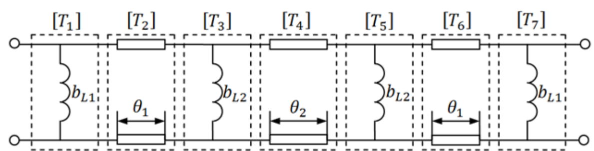

Fig. 3. Equivalent circuit of a waveguide with four inductive irises

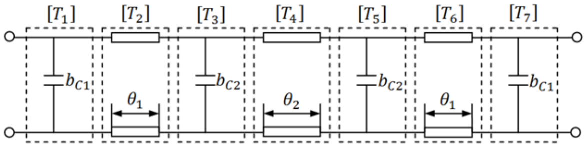

Fig. 4. Equivalent circuit of a waveguide with four capacitive irises

We use the formulas of reactive conductivities of irises in a rectangular waveguide [56], taking into account the influence of higher types of waves

$$b_L = -\frac{2\pi}{a\cdot\beta}\cdot\left[ctg\left(\frac{\pi\cdot d}{2a}\right)\right]^2\cdot \left[1+\frac{a\cdot\gamma_1-3\pi}{4\pi}\cdot\left[\sin\left(\frac{\pi\cdot d}{a}\right)\right]^2\right]; \quad (8)$$

$$b_C = \frac{4\beta b}{\pi}\cdot\left[\ln\left(\cos ec\left(\frac{\pi\cdot d}{2a}\right)\right)+ \left(\frac{2\pi}{a\cdot\gamma_2}-1\right)\cdot\left(\cos\left(\frac{\pi\cdot d}{2a}\right)\right)^4\right], \quad (9)$$

where

$$\gamma_1=\sqrt{\left(\frac{3\pi}{a}\right)^2-k_0^2};\qquad \gamma_2=\sqrt{\left(\frac{2\pi}{b}\right)^2-\beta^2};$$

$$\beta=\sqrt{k_0^2-\left(\frac{\pi}{a}\right)^2};\qquad k_0=\frac{2\pi}{\lambda_0}=\frac{2\pi f}{c},$$

where a and b are the lengths of the wide and narrow walls of the rectangular waveguide expressed in millimeters; d is the width of the gap or iris window expressed in millimeters; k_0 is wave number in vacuum; β is the propagation constant of the fundamental mode H_{10} in a rectangular waveguide. In the case of a square waveguide $a = b$.

The size of the irises window (Fig. 5) is determined by the value of the iris height h

$$d = a - 2\cdot h. \quad (10)$$

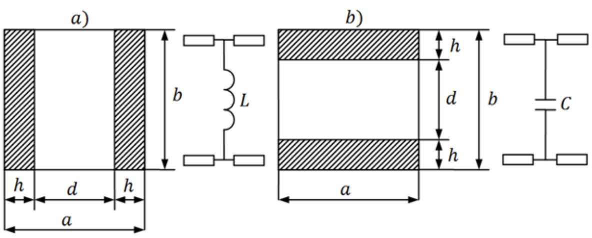

Fig. 5. Inductive and capacitive irises in a rectangular waveguide

Differential phase shift, axial ratio, crosspolar discrimination (XPD), voltage standing wave ratio (VSWR) are the main electromagnetic characteristics of the polarizer.

The differential phase shift at the output of the polarizer is determined as follows

$$\Delta\phi = \phi_L - \phi_C = \arg(S_{\sum 21L}) - \arg(S_{\sum 21C}). \quad (11)$$

VSWR of the polarizer is determined by the following formula

$$VSWR = \frac{1+\left|S_{\sum 11}\right|}{1-\left|S_{\sum 11}\right|}. \quad (12)$$

The axial ratio can be calculated using the modules of expressions (6) [57]:

$$r\ (\mathrm{dB}) = 10\lg\frac{A^2+B^2+\sqrt{A^4+B^4+2A^2B^2\cos(2\Delta\phi)}}{A^2+B^2-\sqrt{A^4+B^4+2A^2B^2\cos(2\Delta\phi)}}, \quad (13)$$

where $A = |S_{\sum 21L}|$, $B = |S_{\sum 21C}|$.

XPD of the polarizer is expressed in dB using the following formula [58]

$$\mathrm{XPD}\ (\mathrm{dB}) = 20\lg\left(\frac{10^{0{,}05r}+1}{10^{0{,}05r}-1}\right), \quad (14)$$

where r is the corresponding axial ratio in dB.

Note that the alteration of the amplitudes of the waves at the output of the polarizer is influenced by VSWR of both polarizations. The axial ratio and corresponding XPD are determined simultaneously by the amplitudes of the waves at the polarizer's output and by the differential phase shift.

Depending on the ratio of the amplitudes at the output and the differential phase shift of the polarizer, it is possible to obtain a wave with any polarization type. In the case of a perfect polarizer the VSWR is equal to 1 for both polarizations, and the differential phase shift is 90°. Then the polarizer in the receiving antenna will transform input waves with orthogonal circular polarizations into output waves with orthogonal linear polarizations and vice versa in the transmitting antenna system.

4 Results of the theoretical analysis

Consider the results of the calculation of the mathematical model of the polarizer in the case of thin irises in the C-band 3.4–4.2 GHz. In this frequency range the wall length of the single-mode square waveguide will vary approximately from 44 mm to 71 mm. The value of the wavelength in the waveguide at the center frequency of the band 3.8 GHz is λ_0 =78.9 mm. According to the method suggested in [59] we choose the size of the wall of the square waveguide of the polarizer and the distance between the irises, which is determined by the ratio $l = 0.25\lambda_0$. Next, to provide the required differential phase shift we change the heights of the irises h_1 and h_2. The matching of the structure is obtained by alteration of the distances between the irises.

We plot the curve frequency dependences of electromagnetic characteristics of the investigated polarizer on the basis of a square waveguide with four reactive irises.

In Fig. 6, Fig. 7, Fig. 8, Fig. 9 shows the dependences of the differential phase shift, VSWR, axial ratio, XPD on the frequency, respectively.

Fig. 6 shows that the differential phase shift takes 90° at 3.5 GHz and 4.15 GHz. The maximum deviation of the differential phase shift from 90° is 2.8° at 3.8 GHz.

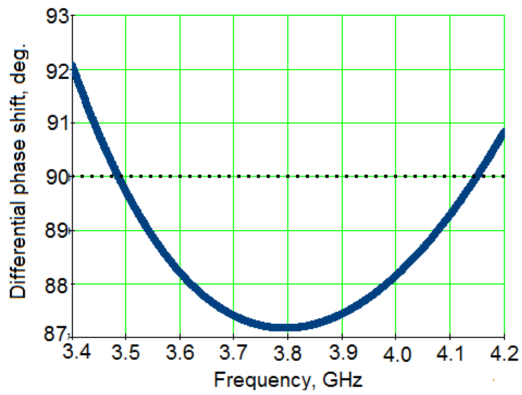

Fig. 6. Dependence of differential phase shift on frequency

Fig. 7 shows that the maximum value of VSWR for horizontal polarization is 1.38 and for vertical polarization is 1.42 at the minimum and maximum frequencies, respectively.

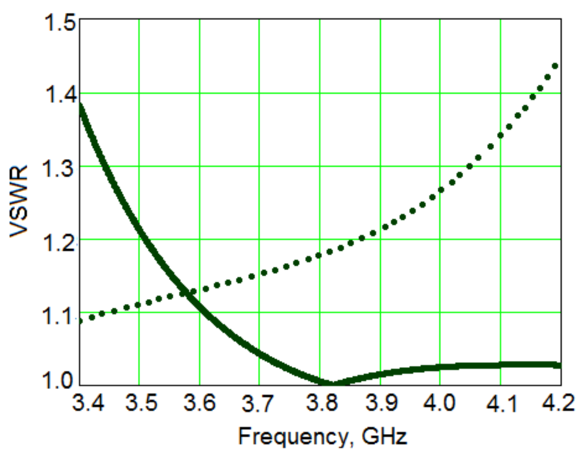

Fig. 7. VSWR vs. frequency for the optimized polarizer solid line – horizontal polarization; dotted line – vertical polarization

Fig. 8 and Fig. 9 show that the maximum value of the axial ratio is 0.51 dB, the maximum value of the XPD is -30.8 dB at a frequency of 3.8 GHz.

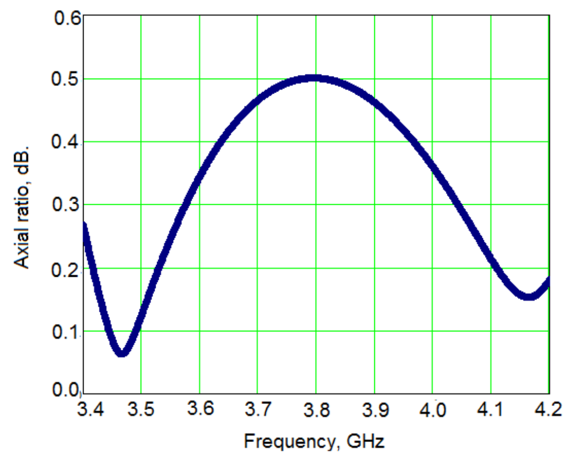

Fig. 8. Dependence of the axial ratio on frequency

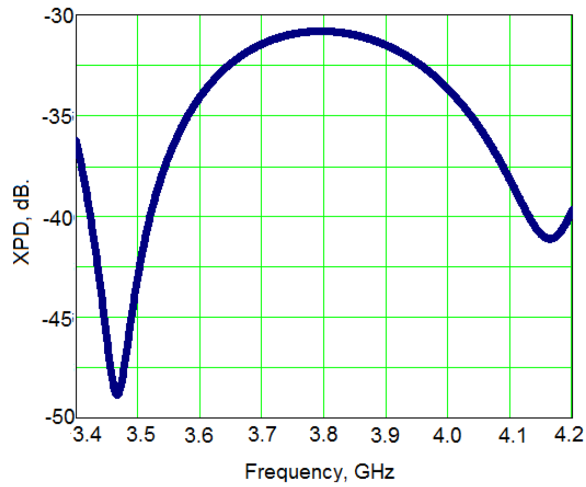

Fig. 9. Dependence of the XPD on frequency

Therefore, in the operating range of 3.4–4.2 GHz, the calculated polarizer based on a square waveguide with four irises provides VSWR for both polarizations less than 1.42. Its differential phase shift lies within the angles of 90° ± 2.8°. The axial ratio is less than 0.50 dB, and XPD is higher than 30.8 dB.

5 Results of simulation by numerical method

The section contains the results of optimization of the design of a polarizer based on a square waveguide with four irises by finite integration technique in the C-band 3.4–4.2 GHz. The created mathematical model was verified by simulation of electromagnetic characteristics of a polarizer using CST Microwave Studio software. The 3-D model of a waveguide iris polarizer, which was developed and simulated in the software, is demonstrated in Fig. 10.

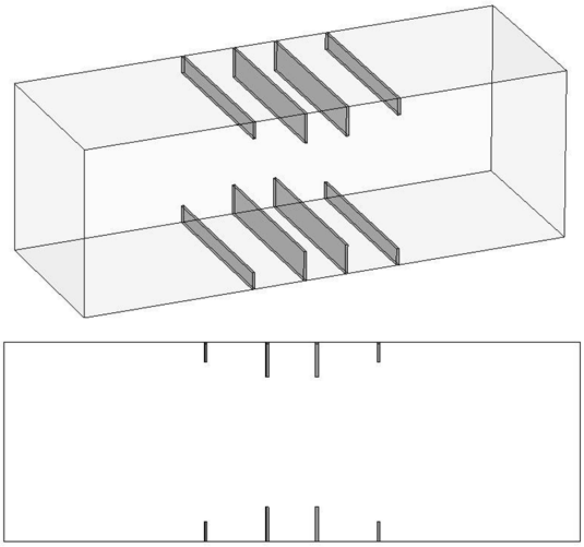

Fig. 10. Dependence of differential phase shift on frequency

In Fig. 11 presents the dependence of the differential phase shift on the frequency for the optimized polarizer.

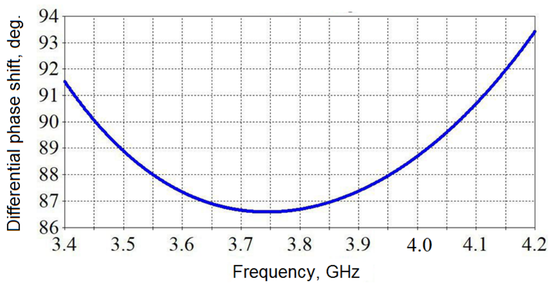

Fig. 11. Dependence of differential phase shift on frequency

In Fig. 11 we see that the maximum deviation of the differential phase shift from 90° is 3.4° at 3.75 GHz and takes the value of 90° at frequencies 3.45 GHz and 4.06 GHz, respectively.

In Fig. 12 shows the frequency dependence of VSWR for the optimized polarizer.

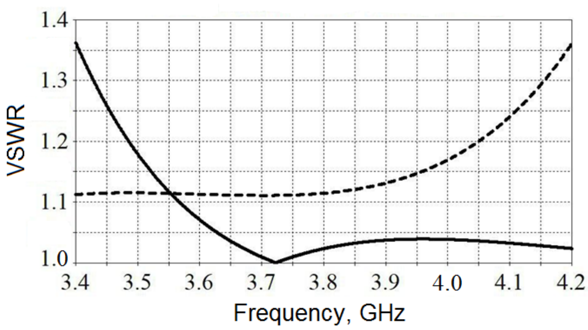

Fig. 12. VSWR vs. frequency for the optimized polarizer solid line – horizontal polarization; dotted line – vertical polarization

In Fig. 12 it is seen that the maximum value of VSWR for both polarizations is 1.36. It is observed at the frequency band edges 3.4 and 4.2 GHz. The minimum value of VSWR of horizontal polarization is 1.0 at a frequency of 3.73 GHz, and for vertical polarization it is 1.11 at a frequency of 3.4 GHz. As one can see in Fig. 12, the increase of frequency results in the decrease of VSWR of the horizontal polarization and the increase of VSWR of the vertical polarization. Using the theory of microwave circuits, this feature can be explained as follows. For the wave with horizontal polarization the irises are inductive and for the wave with vertical polarization they are capacitive. In the first case, the equivalent circuit contains inductances that are connected in parallel. They short the line at low frequencies. In the second case the equivalent circuit contains parallel capacities that short the line at high frequencies.

Fig. 13 contains the dependence of the axial ratio on the frequency for the optimized polarizer.

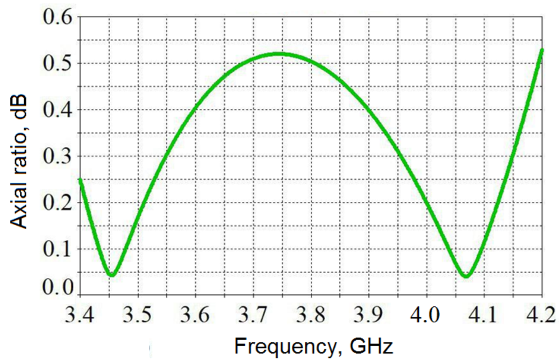

Fig. 13. Axial ratio vs. frequency for the polarizer

Fig. 13 demonstrates that the coefficient of axial ratio in the frequency range from 3.4 GHz to 4.2 GHz does not exceed 0.53 dB. The maximum value of the axial ratio is reached at frequencies of 3.75 GHz and 4.2 GHz, and the minimum value corresponding to the value of 0.085 dB is reached at frequencies of 3.41 GHz and 4.052 GHz.

Fig. 14 contains the dependence of XPD on the frequency for the optimized polarizer.

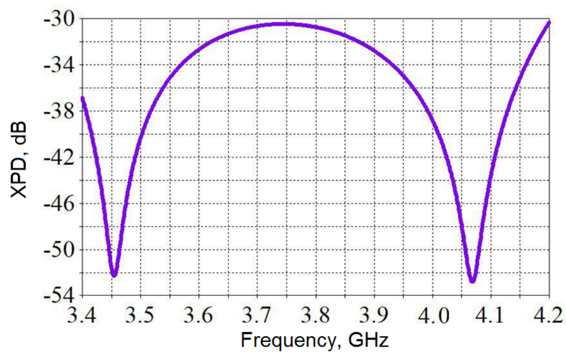

Fig. 14. XPD vs. frequency for the polarizer

Table 1 Sizes of C-band waveguide iris polarizer

	Size name	Development method	CST Microwave Studio
1	Size of square waveguide walls, mm	$a = 64{,}2$	$a = 64{,}2$
2	Height of the lowest irises, mm	$h_1 = 7{,}0$	$h_1 = 6{,}9$
3	Height of the medium irises, mm	$h_2 = 11{,}0$	$h_2 = 11{,}45$
4	Gap between the outer irises, mm	$L_1 = 22{,}4$	$L_1 = 22{,}3$
5	Gap between the inner irises, mm	$L_2 = 24{,}0$	$L_2 = 24{,}2$
6	Thickness of all irises, mm	$w = 1{,}0$	$w = 1{,}0$

Table 2 Characteristics of the optimal C-band waveguide polarizer with irises

	Characteristic	Development method	CST Microwave Studio
1	Differential phase shift	$90° \pm 2,8°$	$90° \pm 3,4°$
2	VSWR	1,42	1,36
3	Axial ratio	0,50 dB	0,53 dB
4	XPD	30,8 dB	30,0 dB

In Fig. 14 we see that the XPD in the frequency range from 3.4 GHz to 4.2 GHz does not exceed 30 dB, which corresponds to the maximum value at frequencies of 3.75 GHz and 4.2 GHz. The minimum value corresponding to the value of 53 dB is reached at frequencies of 3.41 GHz and 4.052 GHz, respectively.

Therefore, in the operating range of 3.4–4.2 GHz, the optimized polarizer based on a square waveguide with four irises provides VSWR for both polarizations less than 1.36. Its differential phase shift lies within the angles of $90° \pm 3.4°$. The axial ratio is less than 0.53 dB, and XPD is higher than 30 dB.

The optimized polarizer sizes are summarized in Table 1 using equivalent circuit model and the numerical method in the C-band 3.4–4.2 GHz.

Table 2 compares the characteristics of the polarizer for the equivalent circuit model and the numerical method.

The results shown in the tables and obtained by two methods are in good agreement. Nevertheless, one can observe in the presented tables that there are small differences in the sizes and characteristics of the polarizer. They are caused by the fact that the developed mathematical model does not take into account the thickness of the irises and the higher-order modes in the structure of a polarizer.

Conclusions

In this research we have developed a rigorous mathematical model of a square waveguide iris polarizer, which allows to calculate its electromagnetic characteristics for the given geometrical sizes of the design. The model allows to vary the heights of the irises and the distances between them in order to provide optimal performance of the polarizer. The irises are simulated as reactive discontinuities, which are inductivities or capacitances depending on the polarization type. Developed model allows to carry out the analysis of influence of the design parameters on the differential phase shift, VSWR for horizontal and vertical polarizations, axial ratio and XPD. Using the mathematical model we have simultaneously provided the required differential phase shift close to 90° and good matching of the polarizer in the operating C-band 3.4–4.2 GHz.

For the first time a simple mathematical model of waveguide polarizers with reactive irises based on a general wave scattering matrix was created. Developed model allows to calculate the electromagnetic characteristics much faster than the finite differences and finite elements methods. The novelty of the created model is the combination of matrix methods for the calculation of microwave circuits performance with accurate variational or mode matching techniques, which allow to obtain equivalent capacitances and inductances of discontinuities in waveguides.

The created mathematical model was verified by comparison with the results of simulation in specialized software based on the finite integration technique. On the whole, very good matching of the results is observed. The deviations of obtained by the mathematical model characteristics from the ones obtained by numerical simulations are caused by the influence of higher order modes and of the thickness of real irises. Therefore, developed mathematical model can be suggested for the analysis and development of waveguide polarizers with different numbers of irises.

The developed in research square waveguide polarizer with 4 irises has a compact design and excellent polarization and matching characteristics. In the operating C-band 3.4–4.2 GHz it provides a differential phase shift $90° \pm 2.8°$. The maximal level of VSWR 1.42 for both polarizations. XPD is higher than 30.8 dB. The corresponding axial ratio is less than 0.50 dB.

Future researches will be dedicated to the improvement of developed equivalent microwave circuit model in order to provide higher accuracy of electromagnetic characteristics calculation. Besides, the analysis and comparison of the designs and performance of waveguide polarizers with larger number of irises are actual problems for the development of modern satellite telecommunication systems.

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Метод еквівалентних мікрохвильових кіл для розробки хвилеводних поляризаторів із діафрагмами

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Збільшення обсягів інформації, що передаються в сучасних супутникових телекомунікаційних системах, вимагає розробки нових технологій обробки сигналів, мікрохвильових пристроїв, антенних систем та методів їх аналізу. Зокрема, для цієї мети широко використовуються поляризаційно-адаптивні антени. Такі антени забезпечують можливість передачі та прийому радіосигналів з поляризацією будь-якого типу. Прилади для обробки поляризації в антенних системах повинні забезпечувати низький рівень коефіцієнта стійних хвиль за напругою для хвиль горизонтальної та вертикальної лінійних поляризацій та високий рівень кросполяризаційної розв'язки одночасно. Тому виникає необхідність вдосконалення конструкцій та методів аналізу сучасних пристроїв поляризаційної обробки. Поляризатори на основі квадратних хвилеводів з діафрагмами широко використовуються завдяки простоті їх конструкції та виготовлення за допомогою фрезерної технології. У статті розглядається нова математична модель хвилеводних поляризаторів з реактивними діафрагмами. Для прикладу застосування моделі ми моделювали та оптимізували поляризатор на основі квадратного хвилеводу з чотирма діафрагмами. Математична модель цього хвилеводного поляризатора була розроблена на основі опису мікрохвильових пристроїв та їх елементів за допомогою матриць розсіювання та передачі. Загальна матриця розсіювання поляризатора отримана аналітично. Основні електромагнітні характеристики поляризатора визначалися на основі елементів цієї матриці. У результаті ми проаналізували основні характеристики моделі, включаючи диференційний фазовий зсув, коефіцієнт стійної хвилі за напругою для вертикальної та горизонтальної поляризації, коефіцієнт еліптичності та кросполяризаційну розв'язку. Оптимізація характеристик поляризатора проведена за допомогою розробленої математичної моделі та програмного забезпечення на основі методу скінчених елементів. Оптимальні характеристики та геометричні розміри структури добре узгоджуються, що підтверджує правильність розробленої математичної моделі поляризаторів на основі квадратного хвилеводу із діафрагмами.

Ключові слова: поляризатор; хвилевідний поляризатор; поляризатор з діафрагмами; матриця розсіювання; матриця передачі; диференційний фазовий зсув; коефіцієнт стійної хвилі за напругою; коефіцієнт еліптичності; кросполяризаційна розв'язка

Метод эквивалентных микроволновых схем для разработки волноводных поляризаторов с диафрагмами

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Увеличение объемов информации, передаваемых в современных спутниковых телекоммуникационных системах, требует разработки новых технологий обработки сигналов, микроволновых устройств, антенных систем и методов их анализа. В частности, для этой цели широко используются поляризационно-адаптивные антенны. Такие антенны обеспечивают возможность передачи и приема радиосигналов с поляризацией любого типа. Приборы для обработки поляризации в антенных системах должны обеспечивать низкий уровень коэффициента стоячих волн по напряжению для волн горизонтальной и вертикальной линейных поляризаций и высокий уровень кроссполяризационной развязки одновременно. Поэтому возникает необходимость совершенствования конструкций и методов анализа современных устройств поляризационной обработки.

Поляризаторы на основе квадратных волноводов с диафрагмами широко используются благодаря простоте их конструкции и изготовления с помощью фрезерной технологии. В статье рассматривается новая математическая модель волноводных поляризаторов с реактивными диафрагмами. В качестве примера применения модели мы моделировали и оптимизировали поляризатор на основе квадратного волновода с четырьмя диафрагмами. Математическая модель этого волноводного поляризатора была разработана на основе описания микроволновых устройств и их элементов с помощью матриц рассеяния и передачи. Общая матрица рассеяния поляризатора получена аналитически. Основные электромагнитные характеристики поляризатора определялись на основе элементов этой матрицы.

В результате мы проанализировали основные характеристики модели, включая дифференциальный фазовый сдвиг, коэффициент стоячей волны по напряжению для вертикальной и горизонтальной поляризации, коэффициент эллиптичности и кроссполяризационную развязку. Оптимизация характеристик поляризатора проведена с помощью разработанной математической модели и программного обеспечения на основе метода конечных элементов. Оптимальные характеристики и геометрические размеры структуры хорошо согласуются, что подтверждает правильность разработанной математической модели поляризаторов на основе квадратного волновода с диафрагмами.

Ключевые слова: поляризатор; волноводный поляризатор; поляризатор с диафрагмами; матрица рассеивания; матрица передачи; коэффициент стоячей волны по напряжению; дифференциальный фазовый сдвиг; коэффициент эллиптичности; кроссполяризационная развязка