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A.V. Bulashenko[1*], S.I. Piltyay[1], Ye.I. Kalinichenko[1], O.V. Bulashenko[2]
[1]Igor Sikorsky Kyiv Polytechnic Institute, Kyiv, Ukraine
[2]Ivan Kozhedub Shostka Professional College of Sumy State University, Shostka, Ukraine
[*]corresponding author: a.bulashenko@kpi.ua

TUNABLE POLARIZERS FOR X-BAND RADAR AND TELECOMMUNICATION SYSTEMS

Background. Nowadays processing of signal polarizations is widely applied in modern information and telecommunication radio engineering systems for different purposes. Commonly polarization processing is carried out in polarization adaptive antenna systems. The essential elements of such systems are transformation devices for polarization processing. They perform the transformation of the types of polarization and separate the different types to isolated channels. The most simple, effective, technological and actual for analysis are polarizers based on square waveguides with irises and posts.
Objective. The purpose of this work is to improve the electromagnetic characteristics of an adjustable polarizer by creating a mathematical model of such device. The device must provide optimized polarization and matching characteristics.
Methods. The article presents a mathematical model of a waveguide polarizer with irises and posts by the decomposition method using wave transmission and scattering matrices. The developed model takes into account the influence of the polarizer design parameters on its characteristics.
Results. The article contains the results of calculations based on the developed mathematical model of the polarizer. In addition, the results of modelling of the device using the finite element method are presented for comparison. For the developed waveguide polarizer we have compared the polarization characteristics and the matching.
Conclusions. The created mathematical model allows us to effectively analyse the characteristics when the design parameters change. These parameters include the size of the wall of the square waveguide, the heights of the irises and posts, the distance between them, the thickness of the irises and posts. The developed polarizer is recommended for the application in modern telecommunication and radar systems.
Keywords: polarizer; waveguide with iris; waveguide with post; transfer matrix; scattering matrix; differential phase shift; crosspolar discrimination.

Introduction

Fast progress in modern telecommunication satellite systems and radars encourages an increase in the data volumes transmitted in their wireless channels. In turn, this requires improvement of existing methods of signal processing and creation of new ones. Polarization signal processing is one of the leading methods for this purpose. Modern adaptive antenna systems, which perform polarization processing of signals, contain waveguide polarizers. The electromagnetic characteristics of such devices determine the overall performance of the communication or radar system. Polarization characteristics are very sensitive to the accuracy of manufacture. Therefore, accurate mathematical modelling and optimization of phase and polarization characteristics is an important problem for the development of modern microwave waveguide polarizers and antenna systems based on them.

A great variety of different modern devices of polarization processing are used in military and civilian radar devices. In addition, waveguide polarizers have become widespread in modern satellite telecommunications systems. Waveguide polarizers are created based on circular [1–4], square [5–7] or coaxial structures [8–11]. Polarizing devices are created on the basis of inhomogeneities in the waveguide. There exist developed structures of polarizers based on inhomogeneities with diaphragms [12–17], posts [18–22], septums [23–29] and corrugation [30–31]. There are also a number of designs of polarizers in the form of slots [32–33]. Waveguide polarizers are also widely used in modern 5G systems [34–40].

But all listed structures have disadvantages, such as the complexity of the design and limited bandwidth. Therefore, a polarizer design containing two types of inhomogeneities was proposed. These are irises and posts. The presence of irises in the design allows you to provide a wide operating frequency band. The presence of posts in the design provides the adjustment of the polarizer.

Problem statement

The purpose of the presented article is to optimize the electromagnetic characteristics of a polarizer based on a square waveguide with diaphragms and post by changing the size of its structure. The problem is solved by creating an appropriate mathematical model of the square waveguide polarizer with irises and posts using wave matrices techniques.

Mathematical model of a square waveguide polarizer with irises and posts

The design of the waveguide polarizer is shown in Fig. 1. The structure contains two irises of height h and thickness w, two posts of height h_p and diameter d, the distance between the iris and the post is l.

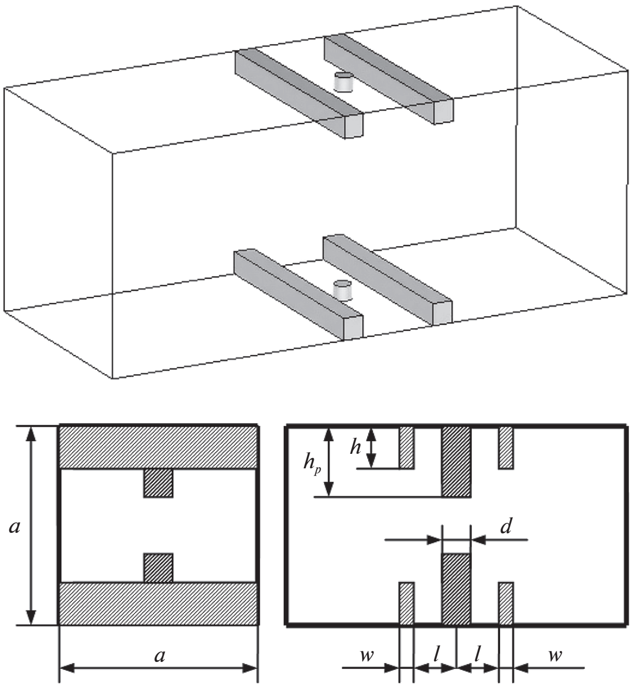


Fig. 1. The design of the polarizer with two irises and two posts

The given design provides the basic polarization characteristics. The cylindrical pin provides adjustment and adjustment of characteristics due to change of length of a post in a waveguide.

According to the theory of microwave circuits [41—43], we present the scheme in the form of separate structural schemes, which are divided into elementary quadrupoles (Fig. 2). Fig. 2, *a* shows a block diagram of a waveguide polarizer with a post and inductive irises connected in parallel. Fig. 2, *b* shows a general block diagram of a waveguide polarizer with a post and capacitive irises connected in parallel.

Let us define the general wave matrix of scattering through elements of the general wave matrix of transfer [44]:

$$\left[\boldsymbol{S}_{\Sigma}\right]=\begin{bmatrix}\boldsymbol{S}_{11\Sigma} & \boldsymbol{S}_{12\Sigma}\\ \boldsymbol{S}_{21\Sigma} & \boldsymbol{S}_{22\Sigma}\end{bmatrix}=\frac{1}{\boldsymbol{T}_{11\Sigma}}\begin{bmatrix}\boldsymbol{T}_{21\Sigma} & |\boldsymbol{T}|\\ 1 & -\boldsymbol{T}_{12\Sigma}\end{bmatrix},$$

where $|T|$ is determinant of the wave matrix of transmission.

For the model with inductive irises and post, the total wave transfer matrix is defined by the expression

$$\left[T_{\Sigma}\right]=\begin{bmatrix}T_{11\Sigma} & T_{12\Sigma}\\ T_{21\Sigma} & T_{22\Sigma}\end{bmatrix}=\left[T_1\right]\cdot\left[T_2\right]\cdot\left[T_3\right],$$

where $\left[T_1\right]$, $\left[T_3\right]$ are matrix describing the iris; $\left[T_2\right]$ is a matrix describing a segment of a regular transmission line.

The wave transmission matrices are determined:

$$\left[T_1\right]=\left[T_3\right]=\begin{bmatrix}T_{11} & T_{12}\\ T_{21} & T_{22}\end{bmatrix},\quad \left[T_2\right]=\begin{bmatrix}e^{j\theta_2} & 0\\ 0 & e^{-j\theta_2}\end{bmatrix},$$

where θ_2 is electric length of a regular transmission line.

The electric length of a regular transmission line

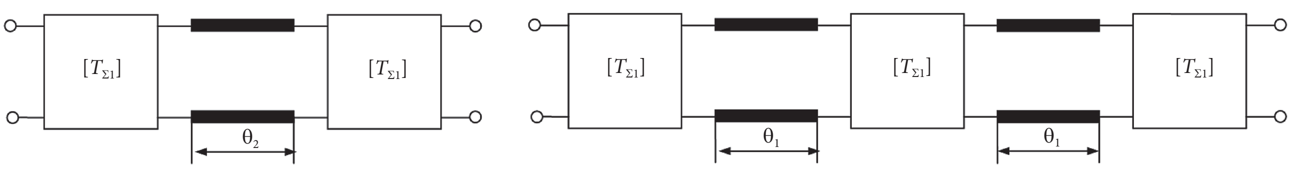
$$\theta_2=2\theta_1=\frac{4\pi l}{\lambda_g},$$

where λ_g is wavelength in the waveguide.

For a model with capacitive irises and a post, the total wave transfer matrix is defined by the expression

$$\left[T_{\Sigma}\right]=\begin{bmatrix}T_{11\Sigma} & T_{12\Sigma}\\ T_{21\Sigma} & T_{22\Sigma}\end{bmatrix}=\left[T_1\right]\cdot\left[T_2\right]\cdot\left[T_3\right]\cdot\left[T_4\right]\cdot\left[T_5\right],$$

where $\left[T_1\right]$ and $\left[T_5\right]$ are matrices describing the diaphragm in the waveguide; $\left[T_3\right]$ is a matrix describing a post in a waveguide; $\left[T_2\right]$ and $\left[T_4\right]$ are matrices describing a segment of a regular transmission line.



a *b*

Fig. 2. Block diagram: models with inductive irises and posts (*a*), models with capacitive irises and posts (*b*)

The wave transmission matrices are determined

$$[T_1]=[T_5]=\begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix},$$

$$[T_2]=[T_4]=\begin{bmatrix} e^{j\theta_1} & 0 \\ 0 & e^{-j\theta_1} \end{bmatrix},\quad [T_3]=\begin{bmatrix} T'_{11} & T'_{12} \\ T'_{21} & T'_{22} \end{bmatrix},$$

where θ_1 is electric length of a regular transmission line.

The electric length of a regular transmission line

$$\theta_1 = \frac{2\pi l}{\lambda_w},$$

where λ_w is wavelength in the waveguide.

The wavelength in the waveguide

$$\lambda_w = \frac{\lambda_0}{\sqrt{1-\left(\frac{\lambda_0}{\lambda_c}\right)^2}},$$

where λ_0 is wavelength in free space; λ_c is cut-off wavelength in a square waveguide.

The wave transmission matrix for the post

$$[T_3]=\begin{bmatrix} T'_{11} & T'_{12} \\ T'_{21} & T'_{22} \end{bmatrix}=\begin{bmatrix} \frac{2+Y_p}{2} & \frac{Y_p}{2} \\ \frac{-Y_p}{2} & \frac{2-Y_p}{2} \end{bmatrix},$$

where Y_p is the conductivity of the post in the waveguide.

The conductivity of the post in the waveguide is determined by the formula [45]

$$Y_p = \frac{j\pi\lambda_0\lambda_g[1-\cos(kh_p)]^2}{a^2k(\mathrm{a}-\mathrm{r})(2+\cos(2kh_p))-\ln(\mathrm{a}/\mathrm{r})\sin(2kh_p)},$$

where a is the length of the wall of a square waveguide; h_p is the height of the post in the waveguide; k is wave number in vacuum; r is post radius.

To take into account the thickness of the iris used equivalent substitution schemes (Fig. 3).

For an inductive iris, the reactive supports of an equivalent circuit (Fig. 3, *a*) are determined by the expressions [46]:

$$Z_a = j\frac{2a}{\lambda_w}\cdot\left(\frac{a}{\pi\cdot D_1}\right)^2;\quad Z_b = -j\frac{a}{8\lambda_w}\cdot\left(\frac{\pi\cdot D_2}{a}\right)^4,$$

where

$$D_1 = \frac{2h}{\sqrt{2}}\cdot\left[1+\frac{w}{\pi\cdot 2h}\ln\left(\frac{4\pi\cdot 2h}{e\cdot w}\right)\right];$$

$$D_2 = \sqrt[4]{\frac{4}{3\pi}w\cdot(2h)^2}\cdot\left(\frac{\pi\cdot D_2}{a}\right)^4,$$

where a is the size of the large wall of the waveguide; w is iris thickness; h is iris height.

To calculate the parameters of the wave matrix transmission of such a scheme using formulas [47]

$$t_{11} = \frac{z_2(z_1+1)+(z_3+1)(z_1+z_2+1)}{2z_2};$$

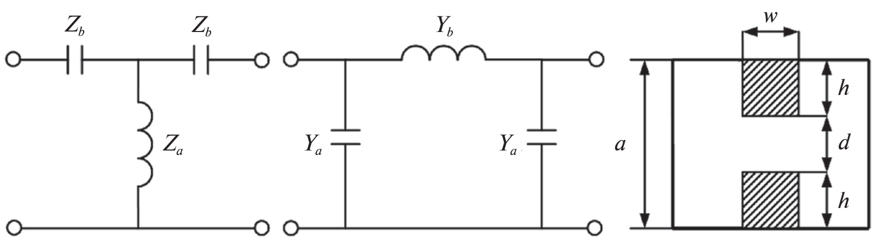
$$t_{12} = \frac{(1-z_3)(z_1+z_2+1)-z_2(z_1+1)}{2z_2};$$

$$t_{21} = \frac{z_2(z_1-1)+(z_3+1)(z_1+z_3-1)}{2z_2};\quad t_{22} = \frac{1+t_{12}t_{21}}{t_{11}},$$

where

$$z_1 = Z_a + Z_b,\quad z_2 = Z_a,\quad z_3 = Z_a + Z_b.$$

For a capacitive iris, the reactive conductivities of an equivalent circuit (Fig. 3, *b*) are determined by the expressions [46]:



a *b*

Fig. 3. Equivalent circuit for inductive (*a*) and capacitive (*b*) irises

$$Y_a = j\left[b_1 + \frac{a}{d}\cdot \mathrm{tg}\left(\frac{\pi\cdot w}{\lambda_w}\right)\right]; \quad Y_b = -j\frac{a}{d}\cdot \csc\left(\frac{2\pi\cdot w}{\lambda_w}\right),$$

where

$$b_1 = \frac{a}{\lambda_g}\cdot\left[\left(\frac{\pi\cdot 2h}{2a}\cdot g\right)+\frac{1}{6}\left(\frac{\pi\cdot 2h}{2a}\cdot g\right)- -\frac{\pi}{2}\cdot\frac{2h}{a}\cdot\frac{w}{d}+\frac{3}{2}\left(\frac{a}{\lambda_w}\right)^2\cdot\left(\frac{\pi\cdot 2h}{2a}\right)^4\right],$$

$$g = 1+\frac{w}{\pi\cdot 2h}\cdot\ln\left(\frac{4\pi}{e}+\frac{2h}{w}\right),$$

where a is the size of the large wall of the waveguide; w is iris thickness; h is iris height.

To calculate the parameters of the wave matrix transmission of such a scheme using formulas [47]

$$t_{11} = \frac{z_1 z_2 z_3 + z_1(z_2+z_3)+z_3(z_1+z_2)+(z_1+z_2+z_3)}{2z_1 z_3};$$

$$t_{12} = \frac{(1-z_3)(z_1+z_2+1)-z_2(z_1+1)}{2z_2};$$

$$t_{21} = \frac{z_2(z_1-1)+(z_3+1)(z_1+z_3-1)}{2z_2};$$

$$t_{22} = \frac{1+t_{12}t_{21}}{t_{11}}.$$

The characteristics of the polarizer are as follows: phase, matching and polarization. Phase and matching are the differential phase shift and the voltage state wave ratio (VSWR). The polarization characteristics of the polarizer are the axial ratio and the crosspolar discrimination (CPD).

Differential phase shift is determined by the expression

$$\Delta\varphi = \varphi_{\Sigma 21.L} - \varphi_{\Sigma 21.C},$$

where $\varphi_{\Sigma 21.L}$ is phase of the parameter $S_{21\Sigma L}$ of the general wave scattering matrix for the model with inductances; $\varphi_{\Sigma 21.C}$ is phase of the parameter $S_{21\Sigma C}$ of the total wave scattering matrix for the model with capacitances.

VSWR horizontal and vertical polarization is determined by the formula:

$$VSWR_L = \frac{1+|S_{\Sigma 11.L}|}{1-|S_{\Sigma 11.L}|}, \quad VSWR_C = \frac{1+|S_{\Sigma 11.C}|}{1-|S_{\Sigma 11.C}|}.$$

The axial ratio is determined in dB [48]:

$$k = 10\log\left[\frac{X+Y+\sqrt{X^2+Y^2+2X\cdot Y}}{X+Y-\sqrt{X^2+Y^2+2X\cdot Y}}\right].$$

where

$$X = |S_{\Sigma 11.L}|^2, \; Y = |S_{\Sigma 11.C}|^2$$

CPD is calculated by the formula in dB:

$$CPD = 20\lg\left(\frac{10^{0.05k}+1}{10^{0.05k}-1}\right).$$

Analysis of the developed mathematical model

Let us investigate the electromagnetic characteristics of the mathematical model of a waveguide polarizer in the X-frequency range from 7.7 GHz to 8.5 GHz.

Using our model, changing the height of the apertures h and pin h_p, we achieve the required differential phase shift. To ensure a given match, adjust the distance between the diaphragms l. These changes must be made at the optimal diaphragm thickness. At this frequency we achieve optimal coordination with a small deviation of the differential phase shift from 90°.

Figs. 4 and 5 present the characteristics of the developed mathematical model of the polarizer based on a square waveguide with two irises and two posts.

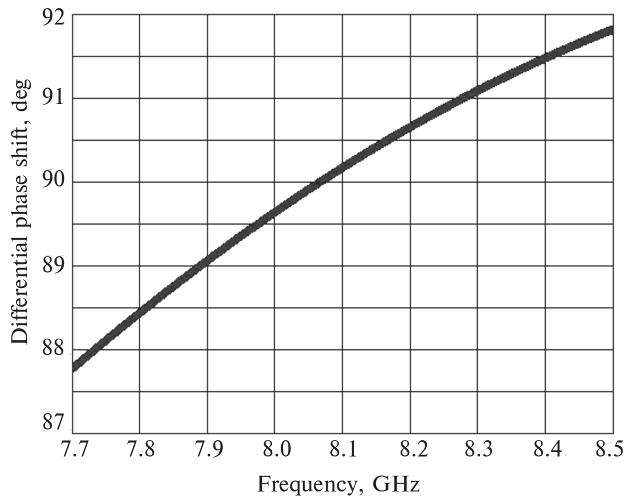


Fig. 4. Dependence of differential phase shift on frequency

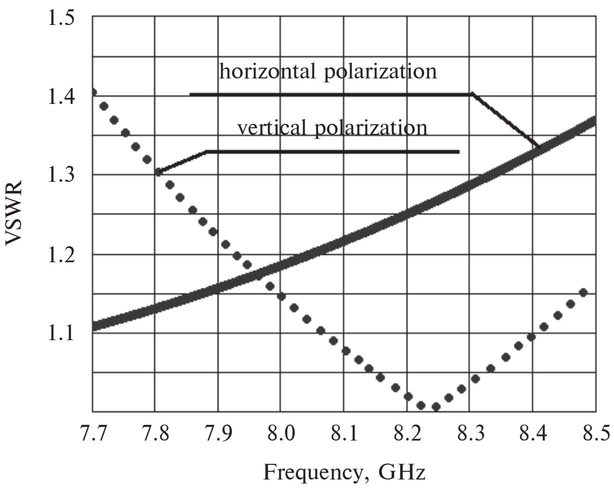


Fig. 5. Dependence of VSWR on frequency

Fig. 4 demonstrates that the maximum deviation of the differential phase shift from 90° is 2.3°. Fig. 5 shows that the maximum value of VSWR for both polarizations is 1.41.

Figs. 6 and 7 present the polarization characteristics of the developed mathematical model of the polarizer based on a square waveguide with two irises and two posts

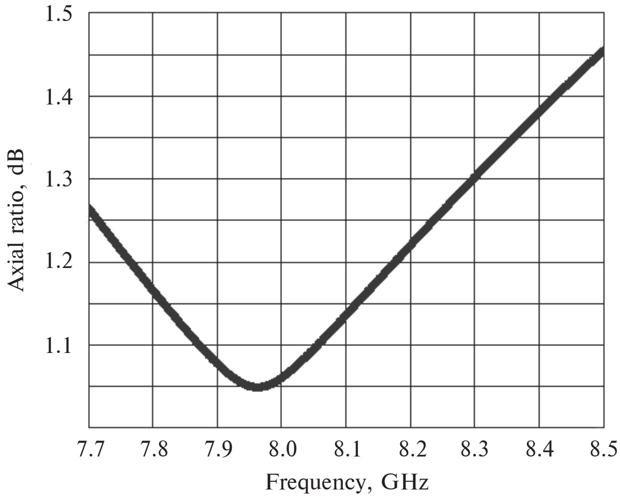


Fig. 6. Dependence of the axial ratio on frequency

Fig. 6 contains the dependence of the axial ratio on the frequency, and Fig. 7 contains the dependence of the VSWR on the frequency. In Fig. 5 we see that at a frequency of 8.5 GHz the axial ratio acquires its maximum value of 0.45 dB. Also, the CPD acquires a maximum value of 30 dB at this frequency.

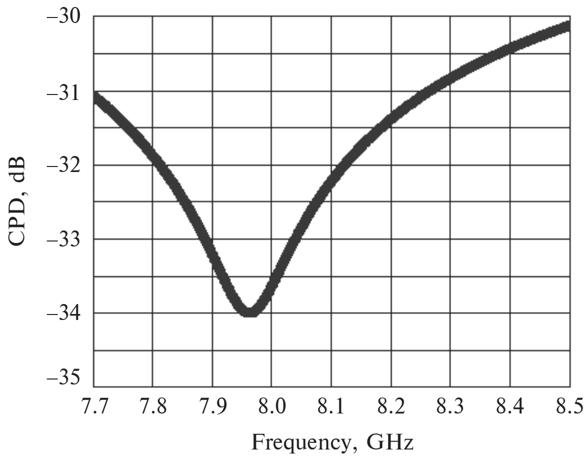


Fig. 7. Dependence of CPD on frequency

Thus, the proposed mathematical model in the X-band 7.7–8.5 GHz for a polarizer based on a square waveguide with two irises and two post provides the following characteristics: VSWR for horizontal and vertical polarization is less than 1.41, differential phase shift is within 90° ± 2.3°, axial ratio is less than 0.45 dB, crosspolar discrimination is higher than 30 dB.

Analysis of optimization results

Let us investigate the electromagnetic characteristics of a numerical model based on the finite element method in frequency domain [49–51] of a waveguide polarizer in the X-frequency range from 7.7 GHz to 8.5 GHz.

Fig. 8 shows the phase and matching characteristics of the polarizer. Fig. 8 contains the dependence of the differential phase shift on the frequency, and Fig. 9 contains the dependence of VSWR on the frequency in the operating frequency range from 7.7 GHz to 8.5 GHz of the studied prototype.

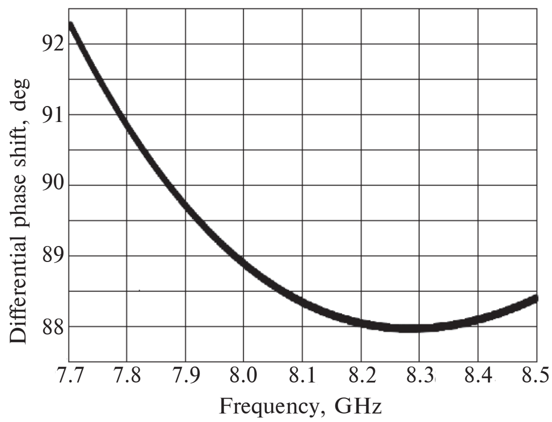


Fig. 8. Dependence of differential phase shift on frequency

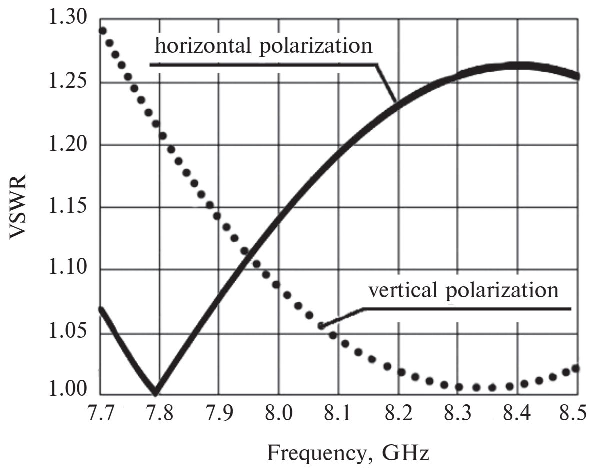


Fig. 9. VSWR frequency dependence for horizontal and vertical polarization

Fig. 8 shows that the maximum deviation of the differential phase shift from 90° is 2.3°. Fig. 9 shows that the maximum value of VSWR for both polarizations is 1.29.

Figs. 10 and 11 show the polarization characteristics of the device in the operating frequency range from 7.7 GHz to 8.5 GHz. Fig. 10 contains the dependence of the axial ratio on the frequency, and Fig. 11 contains the dependence of the CPD on the frequency. In Fig. 10 we see that at the frequency of 8.45 GHz the axial ratio acquires its maximum value of 0.4 dB. Also the CPD acquires a maximum value of 29 dB at this frequency.

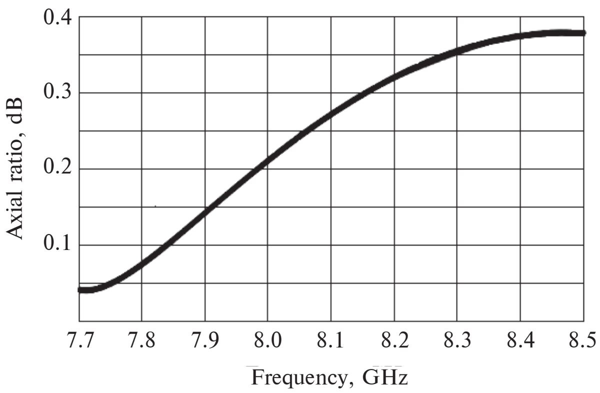


Fig. 10. Dependence of the axial ratio on frequency

Such characteristics provide the optimal design of the polarizer, which are presented in Table 1.

***Table* 1.** Optimal characteristics of the polarizer

a, mm	*w*, mm	*l*, mm	*h*, mm	*hp*, mm	*d*, mm
28.9	3.1	5.3	2.60	2.65	2.4

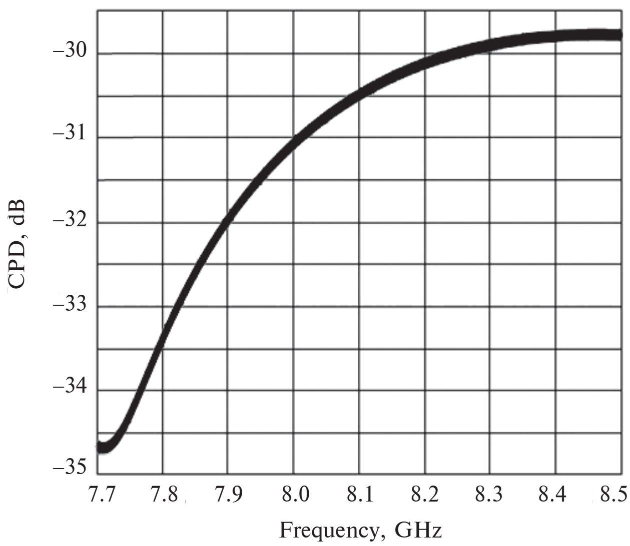


Fig. 11. Dependence of CPD on frequency

As we can see, the matching and polarization characteristics of the mathematical model and the numerical model by the finite element method coincide with the corresponding accuracy.

Therefore, the developed tunable waveguide polarizer simultaneously provides good matching and polarization characteristics. The range of change of the differential phase shift is 90° ± 2.3°. The polarizer provides VSWR 1.29, axial ratio 0.45 dB, CPD is 30 dB.

Conclusions

A new tunable waveguide polarizer has been suggested and developed. In the article we have created mathematical model of this type of polarizer based on a square waveguide with two irises and two posts. Theoretical model takes into account the influence of all design parameters on the polarization and matching characteristics of the waveguide polarizer. The developed model allows performing accurate optimization of the device. Optimal matching and polarization characteristics were achieved in the frequency range from 7.7 GHz to 8.5 GHz by changing the geometric dimensions of the structure. In addition, created mathematical model allows taking into account the influence of the height of irises and posts, the distances between them and their thickness on the electromagnetic characteristics of the polarizer. Therefore, the model can be recommended for the analysis and optimization of new tunable microwave polarizers based on waveguides with different numbers of irises and posts in the structure. Future research will focus on the development of the analytical model, which takes into account more reactive elements and more higher order modes.

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А.В. Булашенко, С.І. Пільтяй, Є.І. Калініченко, О.В. Булашенко

РЕГУЛЬОВАНИЙ ПОЛЯРИЗАТОР Х-ДІАПАЗОНУ ДЛЯ РАДАРНИХ І ТЕЛЕКОМУНІКАЦІЙНИХ СИСТЕМ

Проблематика. У сучасних інформаційно-телекомунікаційних системах широко застосовують поляризаційне оброблення сигналів, яке зазвичай здійснюють у поляризаційних адаптивних антенних системах. Ключовими елементами таких систем є хвилевідні поляризатори, електромагнітні характеристики яких визначають загальну ефективність системи зв›язку або радара. Найбільш простими, ефективними, технологічними й актуальними для аналізу є поляризатори на основі квадратних хвилеводів із діафрагмами та штирями.

Мета дослідження. Покращити електромагнітні характеристики регульованого поляризатора на основі квадратного хвилевода з діафрагмами і штирями. Пристрій має забезпечувати оптимальні поляризаційні й узгоджувальні характеристики.

Методика реалізації. Створення математичної моделі хвилевідного поляризатора з діафрагмами та штирями методом декомпозиції з використанням хвильових матриць передачі та розсіювання. Оптимізація конструкції поляризатора на основі розробленої моделі.

Результати дослідження. Створено математичну модель регульованого поляризатора на основі квадратного хвилеводу з двома діафрагмами та двома штирями. Запропоновано новий регульований хвилевідний поляризатор. Порівняно результати розрахунків поляризаційних й узгоджувальних характеристик розробленого поляризатора на основі запропонованої математичної моделі з результатами розрахунків методом скінченних елементів.

Висновки. Створена математична модель дає змогу ефективно аналізувати зміну характеристик поляризатора за зміни його параметрів: ширини стінки квадратного хвилеводу, товщини та висоти діафрагм і штирів, а також відстаней між ними. Розроблений поляризатор можна рекомендувати до застосування в сучасних телекомунікаційних і радіолокаційних системах.

Ключові слова: поляризатор; хвилевід із діафрагмою; хвилевід зі штирем; матриця передачі; матриця розсіювання; диференційний фазовий зсув; кросполяризаційна розв'язка.

А.В. Булашенко, С.И. Пильтяй, Е.И. Калиниченко, А.В. Булашенко

РЕГУЛИРУЕМЫЙ ПОЛЯРИЗАТОР Х-ДИАПАЗОНА ДЛЯ РАДАРНЫХ И ТЕЛЕКОММУНИКАЦИОННЫХ СИСТЕМ

Проблематика. В современных информационно-телекоммуникационных системах широко применяют поляризационную обработку сигналов, которую обычно осуществляют в поляризационных адаптивных антенных системах. Ключевыми элементами таких систем являются волноводные поляризаторы, электромагнитные характеристики которых определяют общую эффективность системы связи или радара. Наиболее простыми, эффективными, технологичными и актуальными для анализа являются поляризаторы на основе квадратных волноводов с диафрагмами и штырями.

Цель исследования. Улучшить электромагнитные характеристики регулируемого поляризатора на основе квадратного волновода с диафрагмами и штырями. Устройство должно обеспечивать оптимальные поляризационные и согласующие характеристики.

Методика реализации. Создание математической модели волноводного поляризатора с диафрагмами и штырями методом декомпозиции с использованием волновых матриц передачи и рассеивания. Оптимизация конструкции поляризатора на основе разработанной модели.

Результаты исследования. Создана математическая модель регулируемого поляризатора на основе квадратного волновода с двумя диафрагмами и двумя штырями. Предложен новый перестраиваемый волноводный поляризатор. Выполнено сравнение результатов расчетов поляризационных и согласующих характеристик разработанного волноводного поляризатора на основе предложенной модели с результатами расчетов методом конечных элементов.

Выводы. Созданная математическая модель позволяет эффективно анализировать изменение характеристик поляризатора при изменении его параметров: ширины стенки квадратного волновода, толщины и высоты диафрагм и штырей, а также расстояний между ними. Разработанный поляризатор может быть рекомендован к применению в современных телекоммуникационных и радиолокационных системах.

Ключевые слова: поляризатор; волновод с диафрагмой; волновод со штырем; матрица передачи; матрица рассеивания; дифференциальный фазовый сдвиг; кроссполяризационная развязка.

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