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SIMULATION OF COMPACT POLARIZERS FOR SATELLITE TELECOMMUNICATION SYSTEMS WITH THE ACCOUNT OF THICKNESS OF IRISES

Background. One of the main problems in modern satellite telecommunication systems is to increase the volume of information transmission with simultaneous preservation of its quality. Key element of such systems is antenna systems with polarization processing, which is carried out using polarizers. Therefore, development of new polarizers and simple techniques for their analysis and optimization are important problems. The most simple, effective, technological and actual for analysis are polarizers based on waveguides with irises.
Objective. The purpose of the paper is to create a mathematical model of the polarizer based on a square waveguide with irises, which allows analyzing the influence of polarizer's design parameters on its electromagnetic characteristics.
Methods. A mathematical model of the waveguide polarizer with irises is created by decomposition technique using transfer and scattering wave matrices. To take into account the irises' thickness their equivalent T- and П-shaped circuits were used.
Results. We have developed mathematical model of the waveguide polarizer with irises, which takes into account their thickness and is based on the complete scattering wave matrix of the waveguide polarizer. The matrix has been obtained using the microwave circuit theory. The main characteristics of the waveguide polarizer were defined using matrix elements. The optimization of characteristics of a polarizer was carried out in the operating Ku-band 10.7–12.8 GHz.
Conclusions. Suggested mathematical model of a waveguide polarizer with irises provides the account of heights of irises, distances between them and their thickness. The results obtained show that this model is simpler and faster for the calculation of electromagnetic characteristics compared to finite elements method, which is often used for analysis of microwave devices for various applications.

Keywords: polarizer; waveguide with irises; transfer matrix; scattering matrix; differential phase shift; voltage standing wave ratio; axial ratio; crosspolar discrimination.

Introduction

Nowadays there is a rapid development of satellite telecommunication systems and the expansion of modern branches of science and technology that actively apply them. Often such systems require an increase of the volumes of information they are able to process and transmit. A key element of most modern satellite telecommunications systems are antenna systems with processing of signal polarization. Such systems use electromagnetic waves with orthogonal circular or linear polarizations. They improve information characteristics of telecommunication systems and increase the level of the received signal under adverse conditions of wave propagation. Polarization-spatial separation of channels provides the necessary characteristics of telecommunication systems. Application of the advantages of antennas with orthogonal polarizations in satellite telecommunication systems allows increasing their efficiency and information capacity [1].

Polarization processing units and devices for separation of signals with orthogonal polarizations are main elements of antenna systems with orthogonal polarizations. Such devices are used to solve problems of theory of detection and recognition of objects and investigate many phenomena of nature [2]. Such problems include prediction of the intensity of rainfalls, measuring the parameters of ice and snow cover, estimation of the parameters of icebergs, assessing the conditions of crops cultivation and many others.

The main types of signal polarization processing devices are based on structures with posts [3–5], ridged structures [6] and structures with irises [7, 8]. Ridged structures and structures with irises are used to create broadband devices for microwave engineering systems. The analysis of such structures is carried out using various analytical methods. Such methods include mode matching technique [9], transverse field-matching technique [10–12], magnetic field integral equation technique [13], and integral equations technique [14, 15], in which it is possible to take into account the singularity fields on the edges, which excludes the relativity of convergence of series in the transverse field matching technique [16]. The structures of this type are also analyzed using the wave matrix method [17–20].

All listed above methods have one major drawback, which is the difficulty of calculating the complete structure of electromagnetic fields. Therefore, there is a need to focus on simpler methods based on matrix techniques of microwave circuit analysis. They use scattering and transmission wave matrices. Various microwave filters [21–24] and phase shifters [25–28] are often analyzed using such methods. They take into account the interaction of higher order modes without the application of a numerical optimization process using specialized computer programs.

A large number of scientific articles [29–41], which consider polarizers, contain only the results of computer simulation, the process of which requires a large amount of time. Therefore, there is a need to create a new mathematical method for the analysis of waveguide polarizers based on reactive elements.

Polarizers based on square waveguides with irises provide the best characteristics in wide and ultrawide operating frequency bands. Therefore, such a polarizer design was chosen to develop a mathematical model in our research.

Therefore, it is important to develop a new method for analyzing the characteristics of waveguide polarizers with irises. The new method makes it possible to take into account the thickness of the irises of a polarizer. Developed technique allows to determine all electromagnetic characteristics of the polarizer and does not require much time to perform calculations.

Problem statement

The purpose of the presented article is to improve the electromagnetic characteristics of a square waveguide polarizer with irises by optimizing its design for the operating frequency band. The problem is solved by creating an appropriate mathematical model of the waveguide iris polarizer using wave matrices techniques.

Mathematical model of a waveguide polarizer with irises

To create a mathematical model we consider a simple design of a polarizer based on a square waveguide with two irises. It is presented in Fig. 1. The transverse dimensions of the square waveguide of the polarizer are $a \times a$. The design contains two identical irises with equal heights h, thickness w and distance between them l. We used a square waveguide because it provides better performance in a wide operating frequency band than a circular waveguide.

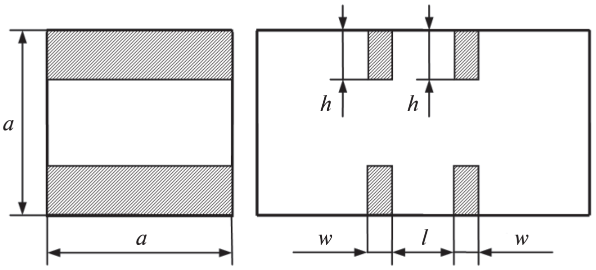


Fig. 1. Internal structure of a square waveguide polarizer with two irises

Using the theory of microwave circuits [34], we present a waveguide polarizer with irises in a general equivalent scheme (Fig. 2).

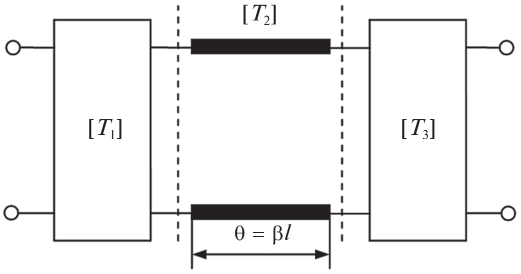


Fig. 2. Equivalent circuit of a waveguide with two reactive elements

Let us divide the equivalent circuit into two-port circuits in the form of 1 section of a regular transmission line and 2 two-port circuits in the form of connected in parallel reactive elements. Each two-port circuit is described by the wave transfer matrix as follows:

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

where θ is the electric length of the equivalent regular transmission line.

The electric length of a regular transmission line is determined by the formula

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

where λ_g is wavelength in the waveguide.

The wavelength in the waveguide is determined by a known formula [34]:

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

where λ_0 is wavelength in free space; λ_c is c cutoff wavelength in a square waveguide.

The wavelength in free space is determined by the formula

$$\lambda_0 = \frac{c}{f},$$

where c is speed of light.

The cutoff wavelength in a square waveguide is determined by the formula

$$\lambda_C = 2a.$$

As a result, the total wave transfer matrix of the polarizer is determined by the expression

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

Let us express the elements of the general scattering matrix through the elements of the transmission matrix:

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

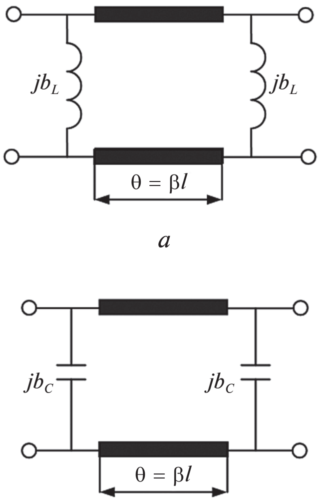
where $|T|$ is determinant of the wave matrix of transmission.

From the scattering matrix we determine its elements through the T-matrix

$$S_{11\Sigma} = \frac{T_{21\Sigma}}{T_{11\Sigma}} = \frac{T_{11}T_{21}e^{j\theta} + T_{21}T_{22}e^{-j\theta}}{T_{11}^2 e^{j\theta} + T_{12}T_{21}e^{-j\theta}};$$

$$S_{21\Sigma} = \frac{1}{T_{11\Sigma}} = \frac{1}{T_{11}^2 e^{j\theta} + T_{12}T_{21}e^{-j\theta}}.$$

For the main wave of horizontal polarization, a simplified equivalent of the polarizer circuit contains inductors that are turned on in parallel (Fig. 3, *a*). For the main wave of vertical polarization of the equivalent circuit contains capacitors that are turned on in parallel (Fig. 3, *b*).



a

b

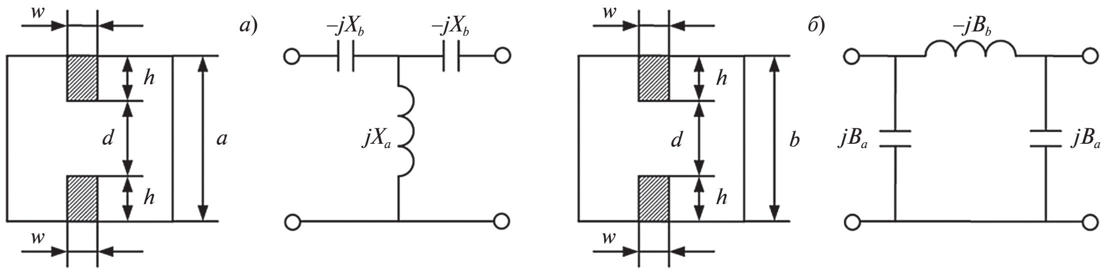
Fig. 3. Equivalent circuit of a waveguide with two reactive elements

To take into account the thickness of the diaphragms, we use more complicated T- and П-shaped equivalent circuits for each capacitive (Fig. 4, *a*) and inductive irises (Fig. 4, *b*).

For an inductive iris, the reactive resistances of an equivalent circuit (Fig. 4, *a*) are determined by the expressions [42]:

$$X_a = \frac{2a}{\lambda_g}\cdot\left(\frac{a}{\pi\cdot D_1}\right)^2;$$

$$X_b = \frac{a}{8\lambda_g}\cdot\left(\frac{\pi\cdot D_2}{a}\right)^4,$$



a

b

Fig. 4. Equivalent circuit for inductive and capacitive irises

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

$$T_{11} = \frac{Z_2(Z_1 + 1) + (Z_3 + 1)(Z_1 + Z_2 + 1)}{2Z_2};$$

$$T_{12} = \frac{(1 - Z_3)(Z_1 + Z_2 + 1) - Z_2(Z_1 + 1)}{2Z_2};$$

$$T_{21} = \frac{Z_2(Z_1 - 1) + (Z_3 + 1)(Z_1 + Z_3 - 1)}{2Z_2};$$

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

For a capacitive iris, the reactive conductivities of an equivalent circuit (Fig. 4, *b*) are determined by the expressions [42]

$$B_a = B_1 + \frac{b}{d} \cdot \mathrm{tg}\left(\frac{\pi \cdot w}{\lambda_g}\right);$$

$$B_b = \frac{b}{d} \cdot \csc\left(\frac{2\pi \cdot w}{\lambda_g}\right),$$

where

$$B_1 = \frac{b}{\lambda_g} \cdot \left[\left(\frac{\pi \cdot 2h}{2b} \cdot g\right) + \frac{1}{6}\left(\frac{\pi \cdot 2h}{2b} \cdot g\right) - \frac{\pi}{2} \cdot \frac{2h}{b} \cdot \frac{w}{d} + \frac{3}{2}\left(\frac{b}{\lambda_g}\right)^2 \cdot \left(\frac{\pi \cdot 2h}{2b}\right)^4\right],$$

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

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

$$T_{11} = \frac{Z_1Z_2Z_3 + Z_1(Z_2 + Z_3) + Z_3(Z_1 + Z_2) + (Z_1 + Z_2 + Z_3)}{2Z_1Z_3};$$

$$T_{12} = \frac{(1 - Z_3)(Z_1 + Z_2 + 1) - Z_2(Z_1 + 1)}{2Z_2};$$

$$T_{21} = \frac{Z_2(Z_1 - 1) + (Z_3 + 1)(Z_1 + Z_3 - 1)}{2Z_2};$$

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

Thus, elements of the general scattering matrix of our mathematical model were formed. Through these elements we determine the main electromagnetic characteristics of a waveguide polarizer with irises.

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

$$\Delta\varphi = \varphi_L - \varphi_C = \arg(\mathrm{S}_{21\Sigma L}) - \arg(\mathrm{S}_{21\Sigma C}),$$

where $\mathrm{S}_{21\Sigma L}$ and $\mathrm{S}_{21\Sigma C}$ are elements of the general scattering matrix in the case of inductive and capacitive irises.

VSWR is calculated by the following formula

$$VSWR = \frac{1 + |S_{11}|}{1 - |S_{11}|}.$$

The axial ratio can be determined by the following expression [43] in dB as follows using logarithmic scale

$$r = 10\lg\frac{A^2 + B^2 + \sqrt{A^4 + B^4 + 2A^2B^2\cos(2\Delta\varphi)}}{A^2 + B^2 - \sqrt{A^4 + B^4 + 2A^2B^2\cos(2\Delta\varphi)}},$$

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

XPD is calculated by the following formula in dB:

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

Analysis of the developed mathematical model

Let us consider the results of the calculation of the mathematical model of the waveguide polarizer in the Ku-band 10.7–12.8 GHz.

To ensure the required differential phase shift we have changed the height of the irises *h*. And to achieve a given matching we have adjusted the distance between the irises. This was performed for the optimal thickness of the irises. In the operating frequency band the optimal matching has been achieved with a small deviation of the differential phase shift from 90°.

Figs. 5—8 show the main electromagnetic characteristics of the polarizer. From Fig. 5 we see that the maximum deviation of the differential phase shift from 90° is 7°.

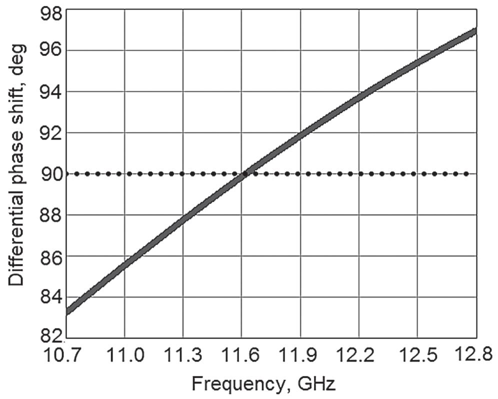


Fig. 5. Dependence of differential phase shift on frequency

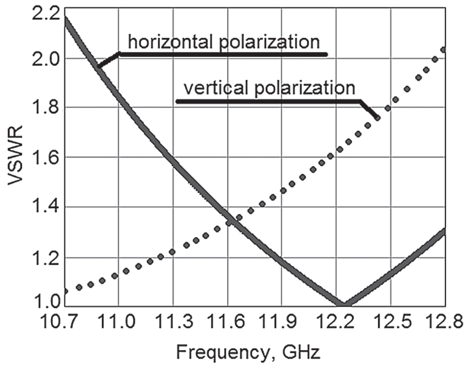


Fig. 6. Dependence of VSWR on frequency

In Fig. 6 we see that the maximum value of VSWR for both polarizations is 2.15 at 10.7 GHz.

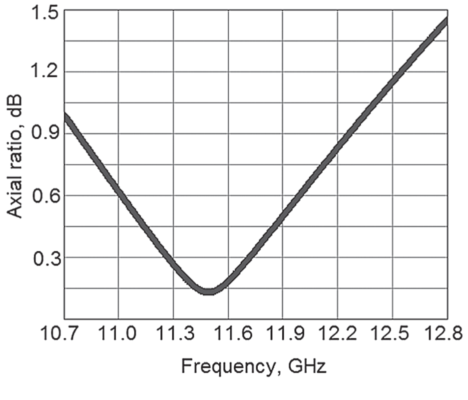


Fig. 7. Dependence of the axial ratio on frequency

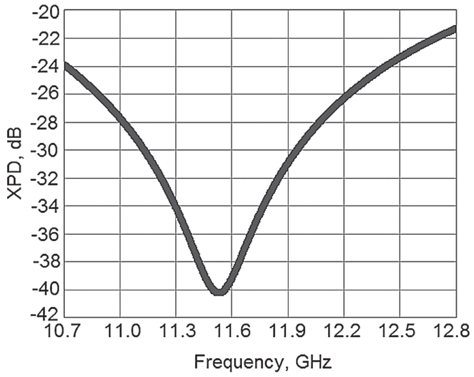


Fig. 8. Dependence of XPD on frequency

From the figures we see that the maximum value of the axial ratio is 1.5 dB, and the crosspolar determination is greater than 21.5 dB.

Thus, the proposed mathematical model in the Ku-band 10.7—12.8 GHz for a polarizer based on a square waveguide with 2 irises provides the following characteristics: VSWR for horizontal and vertical polarization is less than 2.15, differential phase shift is within 90° ± 7.0°, axial ratio is less than 1.5 dB, crosspolar discrimination is higher than 21.5 dB.

Analysis of optimization results

The developed mathematical model of a waveguide polarizer does not take into account some higher order modes. This can result in inaccuracies of calculation of the differential phase shift and polarization characteristics. Consequently, numerical techniques are applied for more accurate estimation of the polarizer's characteristics. Further optimization and modeling of a polarizer based on a square waveguide with two irises were performed by the finite integration technique in the operating Ku-band 10.7—12.8 GHz.

Fig. 9 shows the dependence of the differential phase shift on the frequency. From the figure we see that the maximum deviation of the differential phase shift from 90° is 4.2° at 11.6 GHz.

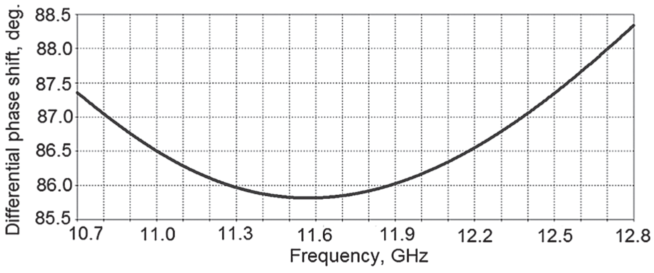


Fig. 9. Dependence of differential phase shift on frequency

Fig. 10 shows the frequency dependence of VSWR for both polarizations. From the figure we see that the maximum value of VSWR for both polarizations is 3.26 at 12.8 GHz.

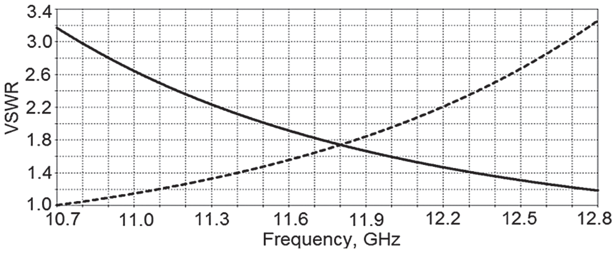


Fig. 10. VSWR frequency dependence for horizontal and vertical polarization: —— – horizontal polarization; ----- – vertical polarization

Figs. 11 and 12 present dependences of the axial ratio and XPD on the frequency. From the figures we see that the maximum value of the axial ratio is 1.43 dB, and the crosspolar discrimination is higher than 21.7 dB.

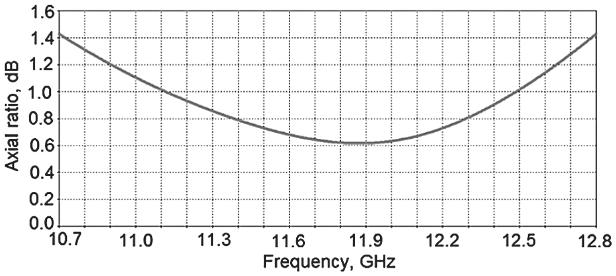


Fig. 11. Dependence of the axial ratio on frequency

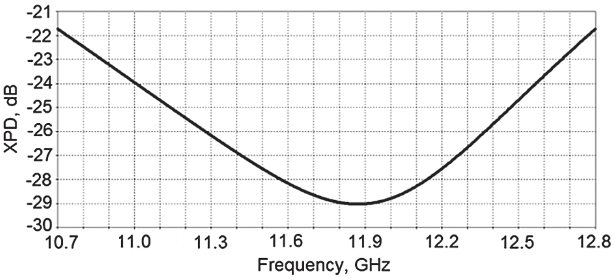


Fig. 12. Dependence of XPD on frequency

Therefore, within the operating frequency range 10.7–12.8 GHz the optimized polarizer based on the square waveguide with 2 irises provides the following characteristics: VSWR for horizontal and vertical polarization is less than 3.26, differential phase shift is within 90° ± 4.2°, axial ratio is less than 1.43 dB, crosspolar discrimination is higher than 21.7 dB.

The optimized parameters of the waveguide polarizer with two irises in the Ku-band 10.7–12.8 GHz are summarized in Table 1.

Table 2 compares the optimized characteristics of the polarizer for the analytical method based on the developed mathematical model and the finite integration technique.

The small difference in sizes and characteristics given in the tables can be explained as follows. The analytical method and the finite integration technique used different numerical methods. In addition, the mathematical model of the analytical method does not take into account all the higher types of waves in the waveguide.

***Table* 1.** Sizes of the optimized waveguide polarizer with irises for the Ku-band for the analytical method and the finite integration technique

	Size name	Analytical method	Finite integration technique
1	Size of the walls of a square waveguide	a = 21.96 mm	a = 21.96 mm
2	Iris height	h = 2.42 mm	h = 3.57 mm
3	Distance between the irises	L = 8.2 mm	L = 4.34 mm
4	Thickness of all irises	w = 2.0 mm	w = 2.96 mm

***Table* 2.** Optimized characteristics of the analytical method and the finite integration technique for a waveguide polarizer with irises for the Ku-band

	Characteristic	Analytical method	Finite integration technique
1	Differential phase shift	90° ± 7.0°	90° ± 4.2°
2	VSWR	2.15	3.26
3	Axial ratio	1.46 dB	1.43 dB
4	XPD	21.5 dB	21.7 dB

Optimized by the created mathematical model structure of the polarizer has improved matching characteristics due to a slight increase in the deviation of the differential phase shift from the required 90°.

Conclusions

In this article we have developed a mathematical model of the polarizer based on a square waveguide with two irises. The mathematical model takes into account the influence of design parameters on the electromagnetic characteristics of the polarizer. It allows achieving better matching performance in the operating frequency band by changing all geometric dimensions of the irises. The novelty of the created model is its account of the influence of the iris thickness on the main characteristics of a waveguide polarizer. Developed mathematical model can be widely applied to create new waveguide polarizers and other devices based on different numbers of irises with different heights.

The proposed mathematical model of the polarizer allows determining the general wave scattering matrix. The main electromagnetic characteristics were determined using the elements of this matrix. Compared with the finite integration technique, the created mathematical model provides an opportunity to quickly analyze and optimize the electromagnetic characteristics by changing the inner sizes of the device. This approach makes it possible to achieve better matching characteristics simultaneously with an acceptable differential phase shift.

In further research it is advisable to focus on the development of more accurate mathematical model that will take into account more irises in the polarizer design and more higher order modes.

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МОДЕЛЮВАННЯ КОМПАКТНИХ ПОЛЯРИЗАТОРІВ ДЛЯ СУПУТНИКОВИХ ТЕЛЕКОМУНІКАЦІЙНИХ СИСТЕМ ІЗ УРАХУВАННЯМ ТОВЩИНИ ДІАФРАГМ

Проблематика. Одним із основних завдань у сучасних супутникових телекомунікаційних системах є збільшення обсягів передачі інформації з одночасним збереженням її якості. Ключовим елементом таких систем є антенні системи із поляризаційним обробленням, яке здійснюють поляризатори. Тож важливим завданням є розробка нових поляризаторів і простих методів їх аналізу та оптимізації. Найбільш простими, ефективними, технологічними та актуальними для аналізу є поляризатори на основі хвилеводів із діафрагмами.

Мета дослідження. Метою роботи є створення математичної моделі поляризатора на основі квадратного хвилеводу з діафрагмами, яка дає можливість аналізувати вплив параметрів конструкції поляризатора на його електромагнітні характеристики.

Методика реалізації. Математична модель хвилевідного поляризатора з діафрагмами створюється методом декомпозиції із використанням хвильових матриць передачі та розсіювання. Для врахування товщини діафрагм використано їх еквівалентні Т- і П-подібні схеми.

Результати дослідження. Розроблено математичну модель хвилевідного поляризатора з діафрагмами, яка враховує їх товщину і ґрунтується на загальній хвильовій матриці розсіювання хвилевідного поляризатора. Ця матриця була отримана на основі теорії мікрохвильових кіл. Через елементи матриці були визначені основні характеристики хвилевідного поляризатора. Проведено оптимізацію характеристик поляризатора для роботи в Ku-діапазоні частот 10,7–12,8 ГГц.

Висновки. Запропонована математична модель хвилевідного поляризатора з діафрагмами забезпечує врахування висот діафрагм, відстаней між ними та їх товщини. Отримані результати показують, що ця модель є простішою та швидшою для розрахунку електромагнітних характеристик, порівняючи з методом скінченних елементів, який часто використовують для аналізу мікрохвильових пристроїв різного призначення.

Ключові слова: поляризатор; хвилевід із діафрагмами; матриця передачі; матриця розсіювання; диференційний фазовий зсув; коефіцієнт стійної хвилі за напругою; коефіцієнт еліптичності; кросполяризаційна розв’язка.

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МОДЕЛИРОВАНИЕ КОМПАКТНЫХ ПОЛЯРИЗАТОРОВ ДЛЯ СПУТНИКОВЫХ ТЕЛЕКОМУНИКАЦИОННЫХ СИСТЕМ С УЧЕТОМ ТОЛЩИНЫ ДИАФРАГМ

Проблематика. Одной из основных задач в современных спутниковых телекоммуникационных системах является увеличение объемов передачи информации с одновременным сохранением ее качества. Ключевым элементом таких систем являются антенные системы с поляризационной обработкой, которую выполняют поляризаторы. Таким образом, важным заданием является разработка новых поляризаторов и простых методов их анализа и оптимизации. Наиболее простыми, эффективными, технологичными и актуальными для анализа являются поляризаторы на основе волноводов с диафрагмами.

Цель исследования. Целью работы является создание математической модели поляризатора на основе квадратного волновода с диафрагмами, которая позволяет анализировать влияние параметров конструкции поляризатора на его электромагнитные характеристики.

Методика реализации. Математическая модель волноводного поляризатора с диафрагмами создается методом декомпозиции с использованием волновых матриц передачи и рассеивания. Для учета толщины диафрагм использовано их эквивалентные Т- и П-подобные схемы.

Результаты исследования. Разработано математическую модель волноводного поляризатора с диафрагмами, которая учитывает их толщину и основывается на общей волновой матрице рассеивания волноводного поляризатора. Эта матрица была получена на основе теории микроволновых цепей. Через элементы матрицы были определены основные характеристики волноводного поляризатора. Проведено оптимизацию характеристик поляризатора для работы в Ku-диапазоне частот 10,7–12,8 ГГц.

Выводы. Предложенная математическая модель волноводного поляризатора с диафрагмами обеспечивает учет высот диафрагм, расстояний между ними и их толщины. Полученные результаты показывают, что данная модель является более простой и быстрой для расчета электромагнитных характеристик по сравнению с методом конечных элементов, который часто используют для анализа микроволновых устройств разного назначения.

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

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