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Wave Matrix Technique for Waveguide Iris Polarizers Simulation. Numerical Results

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Nowadays, one of the progressive and effective directions of modern wireless telecommunication technologies is the creation of antenna systems with adaptive processing of signal polarization. Such antenna systems provide the required characteristics of telecommunication systems for various purposes under the conditions of high noises for one of polarizations and influence of interferences caused by multipath propagation. The key elements of dual-polarization antenna systems are the devices of polarization transformation and separation. These devices are widely used in systems for electronic protection of aircrafts, radar systems for metrological purposes, systems for estimation of the state of crops and soil erosion, systems for the recognition and tracking of aircrafts, satellite information systems.

This article presents the results of numerical analysis of polarization and matching characteristics of a polarizer based on a square waveguide with three irises. The mathematical model of a polarizer is based on the wave matrix technique. Using this technique, the characteristics of the developed polarizer were determined and optimized in the operating X-band 7.25-7.75 GHz, which is used in downlink satellite communication systems. The presented technique allows to study the evolution of the characteristics of polarizers with different dimensions, such as the heights of the irises and the distances between them. The results of this analysis were used to estimate the initial quasi-optimal dimensions of the polarizer to achieve simultaneously the specified matching and small deviations of the differential phase shift from 90° in the whole operating frequency band. The initial dimensions were used for further optimization of the polarizer design by the finite integration technique. Obtained numerically electromagnetic characteristics of the optimized waveguide iris polarizer showed satisfactory agreement with the same characteristics obtained using the developed analytical technique in the whole operating X-band 7.25-7.75 GHz.

Keywords: Microwave devices, Radars, Waveguide polarizer, Iris polarizer, Circular polarization, Differential phase shift, Axial ratio, Crosspolar discrimination.

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1. INTRODUCTION

Polarization adaptive antennas are an important part of modern satellite telecommunication systems. The key elements of such systems are microwave devices for polarization transformation and separation of signals with orthogonal polarizations to isolated waveguide channels. The separation or combination of signals with orthogonal linear polarizations in waveguide feed systems is performed by orthomode transducers [1-3]. The polarization type transformation in antenna systems is usually carried out using waveguide polarizers [4-8]. They convert fundamental electromagnetic modes with orthogonal linear polarizations into waveguide modes with circular polarization and vice versa. The combination of an orthomode transducer and a waveguide polarizer is applied in wideband and ultrawideband antenna systems [5].

The polarization of an electromagnetic wave is determined by the orientation of the electric field vector in the plane, which is orthogonal to the wave propagation direction [9, 10]. The linear polarization of electromagnetic waves can be of vertical, horizontal and inclined type. Other types of polarization are elliptical and circular. Signals, which are transmitted by the electromagnetic waves with circular polarization, have a number of advantages. This leads to their widespread utilization in modern wireless and satellite information systems, as well as in radars for various applications.

The main advantage of signals with circular polarization is the reduction of their magnitude attenuation due to interferences caused by multipath propagation in the real medium [9, 10]. Another advantage is that circularly polarized signals are insensitive to the influence of rotation of the plane of polarization due to the Faraday effect [9, 10]. In addition, when using signals with circular polarization, there is a lack of necessary angular orientation to establish communication between the transmitting and receiving antenna systems [9, 10].

Orthomode transducers and waveguide sections of differential phase shift are necessary elements of dual-polarization antenna systems. Much research is dedicated to the development of these microwave devices [1-8, 11-18]. However, mentioned polarization processing microwave devices do not always meet the requirements of providing wide operating frequency bands in terms of the quality of matching or of the degree of decoupling and isolation of waveguide channels with orthogonal polarizations.

Waveguide septum polarizers [11, 12] and the ones based on irises [4-7] or corrugated waveguides [8] have become the most widespread in modern antenna systems. This is explained by the inherent advantages of mentioned designs. They have small transverse dimen-

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sions and mass, small losses, and provide good manufacturability. Polarizers are developed based on circular [7], coaxial [4] and square waveguides [5, 6, 8]. If we apply rigorous techniques to solve the electromagnetic problem, the analysis of devices based on ridged structures and irises is quite complicated [19]. Therefore, a simpler wave matrix technique from the previous part of the article [20] was used to calculate the characteristics of a microwave waveguide iris polarizer.

In this research, we apply the developed technique to analyze a polarizer based on a square waveguide with irises in order to improve its electromagnetic characteristics and to create an optimal design for the operating X-band 7.25-7.75 GHz.

2. ANALYSIS OF PERFORMANCE OF A SQUARE WAVEGUIDE POLARIZER WITH THREE IRISES

The internal structure of a square waveguide polarizer with three thin irises is presented in Fig. 1. The transverse sizes of the waveguide wall are identical. They are designated as a. The distances between irises are denoted by l, h_1 stands for the heights of lower outer irises, h_2 is the height of the central iris of the waveguide polarizer.

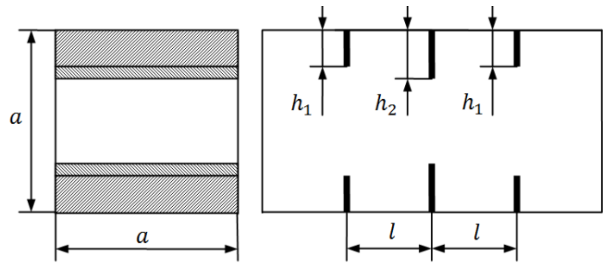

Fig. 1 – The structure of a waveguide polarizer with 3 irises

Using the wave matrix technique, we will analyze and optimize the matching and polarization performance of the square waveguide polarizer with three irises. The main electromagnetic characteristics of the waveguide polarizer for receiving antenna systems are voltage standing wave ratio (VSWR), differential phase shift, axial ratio and crosspolar discrimination (XPD).

The waveguide polarizer must simultaneously provide the propagation of fundamental modes TE_{10} and TE_{01} and the cutoff of TE_{20} and TE_{02} modes. Since the polarizer is developed for the operating frequency band 7.25-7.75 GHz, then the transverse wall size of the square waveguide can be determined using the cutoff frequencies of the mentioned magnetic modes. Consequently, the size a varies from 20.7 to 41.4 mm. The initial value of the size a can be approximately chosen as the average value of this range increased by 5-10 % (32.6-34.2 mm). Therefore, we chose $a = 33$ mm. The center frequency of the operating X-band is $f_0 = 7.5$ GHz. At this frequency, the wavelength λ_g of the fundamental TE_{10} and TE_{01} modes in the square waveguide is equal to 50.3 mm. Then the initial distance between the irises can be approximately estimated as the quarter wavelength in the square waveguide $l = \lambda_g/4 = 12.6$ mm.

As a result, according to the method described in the theoretical part of the article, the initial dimensions of the waveguide polarizer with three irises were determined: the size of the transverse wall of the square waveguide $a = 33$ mm, the heights of the irises $h_1 = 3.2$ mm, $h_2 = 6.4$ mm, and the distances between them $l = 12.6$ mm.

Next, we demonstrate how the optimal values of all sizes were chosen and investigate how the changes in the heights of the irises and the distances between them affect the matching and polarization characteristics of the polarizer.

In order to achieve a differential phase shift close to the required 90º it is necessary to carry out the variation of the heights of all diaphragms h_1, h_2 while maintaining a fixed ratio k between these values. Namely, $h_2 = k \cdot h_1$, where ratio k varies from 1.5 to 2.0. To provide good matching of the structure it is necessary to reduce the initial distance between the irises $l = \lambda_g/4 = 12.6$ mm to the optimal value, which is typically less than the quarter wavelength in the square waveguide of the iris polarizer [4, 5]. For the operating X-band 7.25-7.75 GHz we obtained optimal distance $l = 10.8$ mm.

Fig. 2 presents the differential phase shift between the modes with vertical and horizontal polarizations in the operating frequency band 7.25-7.75 GHz.

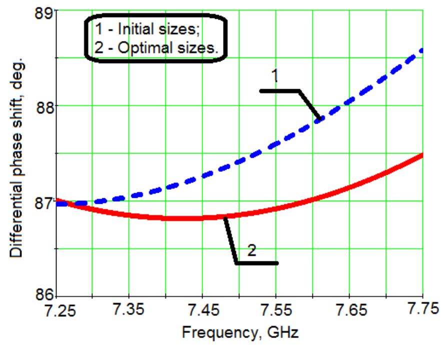

Fig. 2 – Differential phase shift of the waveguide iris polarizer

In Fig. 2, we see that with decreasing distance between irises from 12.6 to 10.8 mm, the differential phase shift moves slightly away from the required 90º and varies from 86.8 to 87.5º. The maximum deviation of the differential phase shift from 90° is 3.2° and it occurs at a frequency of 7.42 GHz, which is close to the center frequency of the operating satellite X-band.

Fig. 3 shows dependences of VSWRs of the polarizer on the frequency for vertical and horizontal polarizations in the operating frequency range 7.25-7.75 GHz.

In Fig. 3, we observe that with decreasing distance between irises from 12.6 to 10.8 mm, the matching of the waveguide polarizer's structure sufficiently improves. For optimal configuration, the VSWR of the fundamental mode TE_{01} with horizontal polarization has a peak level of 1.67 at a frequency of 7.25 GHz. Maximum VSWRs for vertical polarization occur at a frequency of 7.75 GHz. The peak level of VSWRs for vertical polarization decreases from 2.08 to 1.65 for the initial and optimal sizes, respectively.

Fig. 4 demonstrates the axial ratio of the iris polarizer in the operating frequency range 7.25-7.75 GHz.

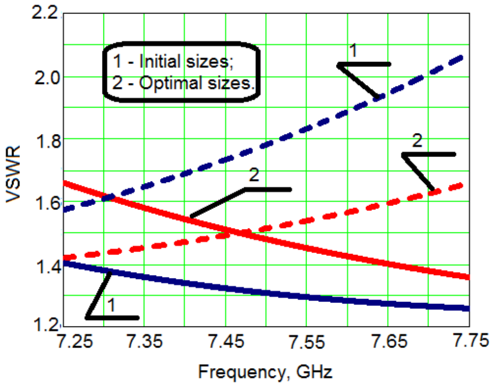

Fig. 3 – Dependences of VSWR of the polarizer on frequency: ——— horizontal polarization; — — — vertical polarization

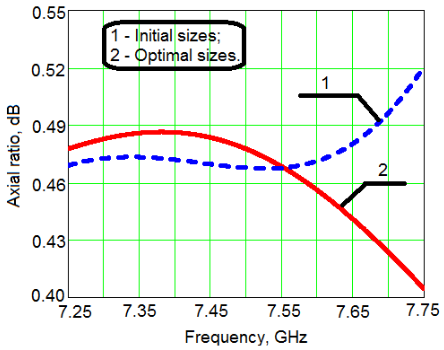

Fig. 4 – Axial ratio vs. frequency for the iris polarizer

In Fig. 4, we see that the decrement of the distances between irises from 12.6 to 10.8 mm leads to a decrease in the axial ratio's peak level from 0.52 to 0.48 dB. This improvement occurs despite the greater differential phase shift deviation from the required 90°. The observed interesting effect can be explained by the fact that the polarization characteristics (namely, axial ratio and crosspolar discrimination) depend simultaneously on phases and magnitudes of the fundamental modes with both orthogonal linear polarizations [20].

Fig. 5 shows the crosspolar discrimination (XPD) of the polarizer in the operating X-band 7.25-7.75 GHz.

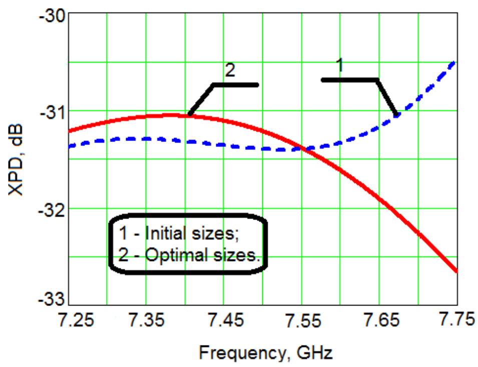

Fig. 5 – XPD vs. frequency for the waveguide iris polarizer

In Fig. 5, it is seen that in the operating frequency band the decrement of distances between irises from 12.6 to 10.8 mm results in the improvement of the XPD from 30.5 to 31.0 dB.

Therefore, the developed in [20] wave matrix technique allows to obtain theoretically the frequency characteristics of waveguide iris polarizers and optimize them for the specified frequency band in order to improve matching and polarization performance of the design.

Obtained theoretically optimal transverse sizes of the square waveguide $a = 33$ mm, the optimal heights of irises $h_1 = 4.51$ mm, $h_2 = 6.95$ mm, the distances between irises $l = 10.8$ mm. The combination of these optimal sizes provides effective performance of the waveguide iris polarizer in the operating X-band 7.25-7.75 GHz. Optimized VSWRs for both polarizations are less than 1.67. The differential phase shift lies within the range 90° ± 3.2°. The axial ratio is less than 0.4 dB. The corresponding XPD is higher than 31 dB.

Table 1 contains the values of the main electromagnetic characteristics of the developed waveguide polarizer for optimal sizes and in the case of simultaneous variation of all geometrical parameters within certain limits.

Table 1 – Characteristics of the X-band waveguide iris polarizer at simultaneous variation of all dimensions

All sizes variation, %	Maximum VSWR	Differential phase shift	Axial ratio, dB	XPD, dB
0	1.67	90° ± 3.2°	0.49	31.0
1	2.10	90° ± 3.0°	0.55	30.0
2	2.15	90° ± 3.0°	0.58	29.6
3	2.20	90° ± 3.0°	0.60	29.3

Presented in Table 1 results allow us to conclude how the simultaneous change of the parameters of the polarizer within 1, 2 or 3 % influences its characteristics. From Table 1, we see that the variation of all geometrical parameters by 1-3 % practically does not influence the differential phase shift. Its deviation from 90° remains equal to 3°. In the case of 1 % variation of all sizes, the axial ratio deteriorates to the value of 0.55 dB and the lowest level of XPD decreases to 30.0 dB. The greatest deterioration is observed for the VSWR, whose peak level increases to 2.10. Therefore, the deviation of all dimensions by more than 1 % is undesirable.

3. RESULTS OF NUMERICAL OPTIMIZATION OF THE WAVEGUIDE IRIS POLARIZER PERFORMANCE

Further accurate simulation of the waveguide iris polarizer performance and optimization of its characteristics were performed using the finite integration technique. The same design of a polarizer based on 3 irises in a square waveguide was considered. The results of numerical simulations are given in this section.

The dimensions, which were obtained by parametric optimization of the waveguide polarizer, are as follows: $a = 33.2$ mm, $h_1 = 4.2$ mm, $h_2 = 6.8$ mm, $l = 11.3$ mm.

Fig. 6 presents the dependences of VSWRs of the optimized polarizer with three irises on the frequency for both polarizations in the operating X-band 7.25-7.75 GHz. In Fig. 6, it is seen that the maximum value of VSWR for both polarizations is 1.66 and it occurs at the lowest frequency of the operating X-band 7.25 GHz.

At higher frequencies, the VSWR of the fundamental mode TE_{01} with horizontal polarization decreases, whereas the VSWR of the fundamental mode TE_{10} with vertical polarization increases. Besides, the maximum of VSWR for the fundamental mode TE_{01} with horizontal polarization is observed at a frequency corresponding to the minimum of VSWR of the fundamental mode TE_{10} of vertical polarization, and vice versa.

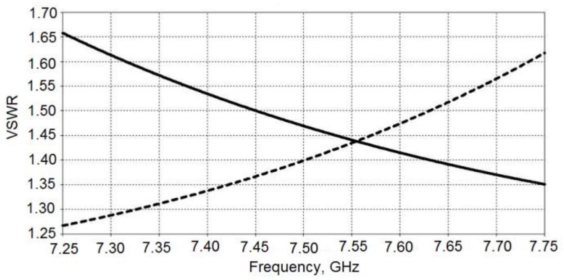

Fig. 6 – VSWR vs. frequency for the optimized iris polarizer: ——— horizontal polarization; — — — vertical polarization

Fig. 7 demonstrates the dependence of the differential phase shift of the optimized square waveguide polarizer with three irises on the frequency in X-band. As one can see in Fig. 7, the differential phase shift is equal to 90° at a frequency of 7.67 GHz. In the operating X-band 7.25-7.75 GHz, the differential phase shift of the square waveguide polarizer with three irises alters from 88.6 to 90.6°. The maximum deviation of the differential phase shift from 90° is 1.4° and it occurs at a frequency of 7.32 GHz, which is close to the minimum frequency of the operating satellite X-band.

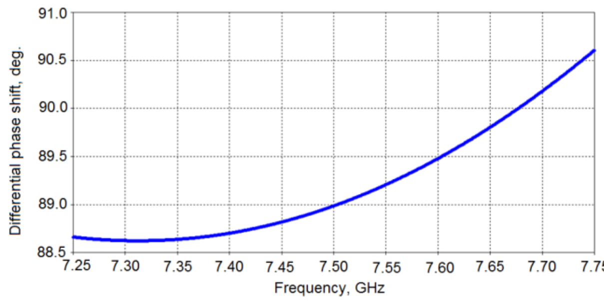

Fig. 7 – Differential phase shift of the polarizer with 3 irises

Therefore, the application of three irises in the structure of a square waveguide polarizer is enough to obtain the differential phase shift, which is quite close to 90° in the 7 % fractional bandwidth. In this case, the main problem is bad matching of the waveguide polarizer with three irises due to a small number of discontinuities in the structure. The occurring reflections from three irises do not compensate each other in the whole 7 % fractional bandwidth. Consequently, in order to improve matching of the square waveguide polarizer, the number of irises must be increased.

The frequency dependences of the axial ratio and XPD of the optimized numerically polarizer based on a square waveguide with three irises in the operating X-band 7.25-7.75 GHz are demonstrated in Fig. 8 and Fig. 9, respectively.

In Fig. 8, it is seen that in the operating frequency band 7.25-7.75 GHz, the axial ratio of the optimized numerically square waveguide polarizer with three irises is less than 0.30 dB. As one can observe in Fig. 9, the corresponding XPD of the optimized waveguide iris polarizer is higher than 35 dB. The maximum of the axial ratio (as well as the lowest XPD) is observed at a frequency of 7.25 GHz, which with high accuracy corresponds to the frequency of the maximum deviation of the differential phase shift of the polarizer from 90°.

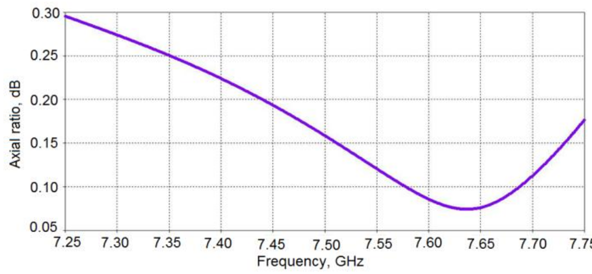

Fig. 8 – Axial ratio vs. frequency of the polarizer with 3 irises

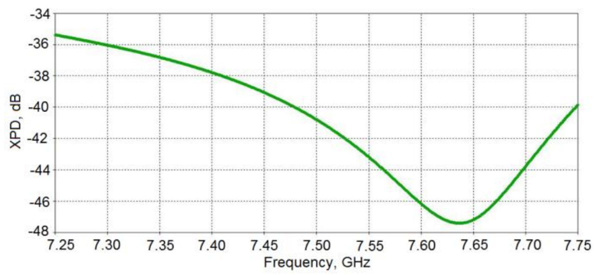

Fig. 9 – XPD vs. frequency of the optimized iris polarizer

Besides, there occurs one prominent minimum of the dependences of the axial ratio and XPD at a frequency of 7.64 GHz, which does not exactly correspond to a differential phase shift of 90°. The difference in these frequencies is caused by a significant distinction in the frequency characteristics of the VSWR of the waveguide polarizer with three irises for the fundamental modes with horizontal and vertical polarizations, as well as by high levels of VSWR within the operating X-band.

Consequently, in the operating frequency band 7.25-7.75 GHz, the optimized square waveguide polarizer with three irises provides VSWRs for both polarizations less than 1.66. The differential phase shift lies within the range of 90° ± 1.6°. The axial ratio is less than 0.30 dB, the corresponding XPD is higher than 35 dB.

4. CONCLUSIONS

In this research, the wave matrix technique was effectively applied for the development, theoretical analysis and optimization of a square waveguide iris polarizer for the operating X-band. The analysis of influence of the geometrical parameters on the electromagnetic performance of the polarizer has been carried out.

Suggested theoretical method allows to simultaneously achieve the best values of VSWR for both polarizations, of axial ratio and XPD by changing the geometrical dimensions of irises and the distances between them. The obtained differential phase shift is close to the required value of 90º. It has been found that the deviation of all dimensions by more than 1 % is undesirable if good matching and polarization characteristics of the waveguide iris polarizer are required simultaneously.

Additional numerical optimization of the waveguide iris polarizer characteristics was performed using the finite integration technique. The dimensions and electromagnetic characteristics of the waveguide iris polarizer, which were obtained by both techniques, are in good agreement. The results of both techniques have slight differences caused by not taking into account the higher-order waveguide modes and the irises thickness by the developed wave matrix technique.

In the operating frequency X-band 7.25-7.75 GHz, the optimized square waveguide polarizer with three irises provides VSWRs for both polarizations less than 1.66. The differential phase shift is 90° ± 1.6°, the axial ratio is less than 0.30 dB, and the corresponding XPD is higher than 35 dB.

Therefore, the developed square waveguide polarizer with three irises combines a compact design, good matching and polarization characteristics. Obtained in this research results can be used for the development and optimization of new waveguide iris polarizers for modern radar and satellite antenna systems.

REFERENCES

1. J.A. Ruiz-Cruz, J.R. Montejo-Garai, C.A. Leal-Sevillano, J.M. Rebollar, *IEEE T. Antenn. Propag.* **66** No 3, 1160 (2018).
2. G. Virone, O.A. Peverini, M. Lumia, M.Z. Farooqui, G. Addamo, R. Trascone, *IEEE Microw. Wirel. Co.* **25** No 2, 85 (2015).
3. F.F. Dubrovka, S.I. Piltyay, *VIII IEEE International Conference on Antenna Theory and Techniques (ICATT)*, art. No 6170737, 176 (Kyiv: IEEE: 2011).
4. F.F. Dubrovka, S.I. Piltyay, *VIX IEEE International Conference on Antenna Theory and Techniques (ICATT)*, art. No 6650816, 473 (Odesa: IEEE: 2013).
5. S.I. Piltyay, *XI IEEE International Conference on Antenna Theory and Techniques (ICATT)*, art. No 7972644, 284 (Kyiv: IEEE: 2017).
6. G. Virone, R. Tascone, O.A. Peverini, G. Addamo, R. Orta, *IEEE Microw. Wirel. Co.* **18** No 8, 509 (2008).
7. G. Bertin, B. Piovano, L. Accatino, M. Mongiardo, *IEEE T. Microw. Theory,* **50** No 4, 1077 (2002).
8. Yu. Tikhov, *IET Microw. Antenna P.* **10** No 2, 147 (2016).
9. W.L. Stutzman, *Polarization in Electromagnetic Systems* (Norwood: Artech House: 2018).
10. W.L. Stutzman, G.A. Thiele, *Antenna Theory and Design* (New Jersey: John Wiley and Sons: 2013).
11. F.F. Dubrovka. S.I. Piltyay, R.R. Dubrovka, M.M. Lytvyn, S.M. Lytvyn, *Radioelectron. Commun. Syst.* **63** No 1, 15 (2020).
12. B. Deutschmann, A.F. Jacob, *IEEE T. Microw. Theory.* **68** No 2, 693 (2020).
13. A.W. Pollak, M.E. Jones, *IEEE Antenn. Wirel. Pr.* **17** No 3, 422 (2018).
14. J. Flygare, M. Pantaleev, *IEEE T. Antenn. Propag.* **68** No 1, 207 (2020).
15. I. Agnihotri, S.K. Sharma, *IEEE Antenn. Wirel. Pr.* **18** No 12, 2726 (2019).
16. C.A. Leal-Sevillano, J.R. Montejo-Garari, J.A. Ruiz-Cruz, J.M. Rebollar, *IEEE T. Microw. Theory* **64** No 3, 724 (2016).
17. W. Zhang, J.-Y. Li, J. Xie, *IEEE T. Antenn. Propag.* **65** No 10, 5623 (2017).
18. G. Mishra, S.K. Sharma, J.S. Chieh, *IEEE T. Antenn. Propag.* **67** No 3, 1904 (2019).
19. F.F. Dubrovka, S.I. Piltyay, *Radioelectron. Commun. Syst.,* **57** No 1, 1 (2014).
20. A.V. Bulashenko, S.I. Piltyay, I.V. Demchenko, *J. Nano-Electron. Phys.* **12** No 6, 06026 (2020).

Метод хвильових матриць для моделювання поляризаторів із діафрагмами. Чисельні результати

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Сьогодні одним з перспективних та ефективних напрямків сучасних телекомунікаційних технологій є створення антенних систем із адаптивним обробленням поляризації сигналів. Такі антенні системи забезпечують необхідні характеристики телекомунікаційних систем різного призначення в умовах високого рівня шумів для однієї з поляризацій та впливу завад, обумовлених багатопроменевим поширенням. Ключовим елементом двополяризаційних антенних систем є пристрої перетворення та розділення поляризацій. Такі пристрої широко використовуються в системах радіоелектронного захисту літальних апаратів, радіолокаційних системах метрологічного призначення, системах оцінки стану посівів сільськогосподарських культур та ерозії ґрунтів, системах розпізнавання та супроводу літальних апаратів, супутникових інформаційних системах.

В статті представлено результати чисельного аналізу поляризаційних характеристик та узгодження поляризатора на основі квадратного хвилеводу із трьома діафрагмами. Математичну модель поляризатора отримано за допомогою методу хвильових матриць. За допомогою цього методу було визначено характеристики розробленого поляризатора та виконано оптимізацію його характеристик у робочому X-діапазоні частот 7,25-7,75 ГГц, який застосовують у радіолініях зв’язку супутникових комунікаційних систем. Представлений метод дозволяє дослідити еволюцію характеристик поляризатора при зміні його розмірів, таких як висоти діафрагм та відстані між ними. Результати цього аналізу було використано для оцінки початкових квазі-оптимальних розмірів поляризатора з метою одночасного забезпечення заданого узгодження та малого відхилення диференційного фазового зсуву від 90° у всьому робочому діапазоні частот. Початкові розміри було використано для подальшої оптимізації конструкції поляризатора за допомогою методу скінченного інтегрування. Отримані чисельним методом електромагнітні характеристики оптимізованого хвилеводного поляризатора із діафрагмами продемонстрували задовільне узгодження з тими ж характеристиками, отриманими за допомогою розробленого аналітичного методу в усьому робочому X-діапазоні частот 7,25-7,75 ГГц.

Ключові слова: Мікрохвильові пристрої, Радари, Хвилеводний поляризатор, Поляризатор із діафрагмами, Колова поляризація, Диференційний фазовий зсув, Коефіцієнт еліптичності, Кросполяризаційна розв'язка.