РАДІОЕЛЕКТРОНІКА
ТА ТЕЛЕКОМУНІКАЦІЇ

RADIO ELECTRONICS
AND TELECOMMUNICATIONS

РАДИОЭЛЕКТРОНИКА
И ТЕЛЕКОММУНИКАЦИИ

COMPACT DIRECTIONAL COUPLERS USING COMBINATION OF MICROSTRIP AND SLOT LINES

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ABSTRACT

Context. Transition of modern electronics to higher frequencies is directly related with an extremely important problem of miniaturization of microwave integrated circuits. Conventional planar structures such as microstrip directional couplers have the feature – their linear dimensions are defined by the wavelength in the transmission lines, so the use of such structures for miniaturization of microwave integrated circuits becomes problematic.

Objective. Using 3D-structures on combinations of transmission lines to study frequency properties of two possible implementations of quarter-wave directional couplers based on a combination of microstrip and slot transmission lines. Obtaining simple analytical expressions for calculating the electrophysical parameters of these directional couplers and confirm their properties by rigorous electrodynamic calculation.

Methods. An even-odd mode decomposition technique and the scattering matrix theory were used to derive simple analytical formulas for calculating impedances of transmission line segments that define the topology of couplers considered.

Results. Electrodynamic modeling of proposed couplers with dispersion and losses in the lines showed that the proposed constructions have better frequency characteristics in comparison with traditional three-branch microstrip directional couplers. It is also shown that the considered designs of couplers have great potential in the selection of the desired electrical characteristics of devices.

Conclusions. The presented compact couplers can find a broad range of applications in mobile communication systems for decoupling of channels, division of power and frequency conversion. The method of transition from planar to three-dimensional structures used in the development of directional couplers on combinations of transmission lines permits not only to create compact devices with desired characteristics but also paves the way for significant decrease in the size and costs of the broad range of electronic equipment utilizing such couplers.

KEYWORDS: Directional couplers, microstip and slot lines, microwave integrated circuits.

NOMENCLATURE

k is the power division ratio between operating ports;
Z_i is the impedance of corresponding line;
λ_i is the wavelength in corresponding line;
S_{ij} is the element of scattering matrix;
W_i is the width of corresponding line.

INTRODUCTION

Microwaves and millimeter-waves are rapidly finding new applications. These include modern mobile communication systems where the problem of miniaturization is of crucial importance. An important part of many microwave circuits are directional couplers on the base of microstrip lines which are used not only as decoupling devices with the function of bridges but also as circuit elements for directional diversion of a certain part of the power from the main line. For consistent mathematical description of such couplers, it is convenient to apply an even-odd mode decomposition technique using symmetry properties of the circuit [1].

It is well known that increasing the number of branches in the coupler leads to better coupler parameters in the frequency band. Moreover, if the condition of equal power division is set which corresponds to the hybrid coupler it is necessary to increase the impedance of end branches to ensure the matching requirements. This fact imposes technological limitations in the implementation of strip structures on substrates with $\varepsilon_r \approx 10$ and therefore in practice two-branch couplers are the most widely used. However if an unequal power division is used instead one can avoid most of the above-mentioned technological limitations as shown in [2]. For the co-directional coupler the power division ratio between operating ports 3 and 4 is defined as

$$k = \frac{\left|S_{31}\right|^2}{\left|S_{41}\right|^2}. \tag{1}$$

Then for a two-branch coupler (Fig. 1) the ratios for determining the impedances of branches will have the form

$$Z_1 = Z_0 \cdot \sqrt{k}; \quad Z_2 = Z_0 \cdot \sqrt{\frac{k}{k+1}}. \tag{2}$$

Here Z_0 is the input impedance.

For a three-branch coupler (Fig. 2) one can implement different relations between the impedances.
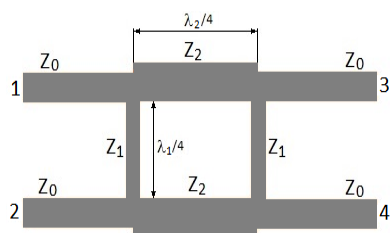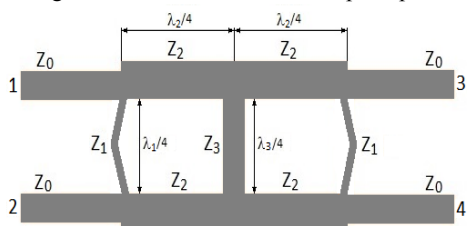

Figure 1 – Two-branch microstrip coupler

Figure 2 – Three-branch microstrip coupler

For example, two options discussed in [2] are:
– option 1:

$$Z_1 = \frac{Z_0}{\sqrt{k+1}-\sqrt{k}}, Z_2 = \frac{Z_0}{\sqrt{2}}, Z_3 = \frac{Z_0\sqrt{k+1}}{2}, \tag{3}$$

– option 2:

$$Z_1 = \frac{Z_0}{\sqrt{k+1}-\sqrt{k}}, Z_2 = Z_0, Z_3 = Z_0\sqrt{k+1}. \tag{4}$$

It should be noted that relations (3) or (4) are not unique. In these formulas, only Z_1 parameter is uniquely determined, and one of the other two parameters of Z_2 or Z_3 (which are related to each other by a certain ratio) can be selected in accordance with technological or other limitations. This means that, for example, the formula for Z_3 in (3) is obtained by choosing $Z_2 = Z_0/\sqrt{2}$, and in (4), the expression for Z_3 is obtained by choosing $Z_2 = Z_0$. With a different choice of Z_2 expressions for Z_3 will be different.

In the case of a four-branch coupler several different relations between the characteristic impedances may also be realized [2].

Fig. 3 shows the frequency dependence of the scattering parameters of two- and four-branch 3 dB lossless directional couplers (quadrature hybrids) in the frequency range $0.5f_0$ up to $1.5f_0$, where f_0 is the operating frequency.
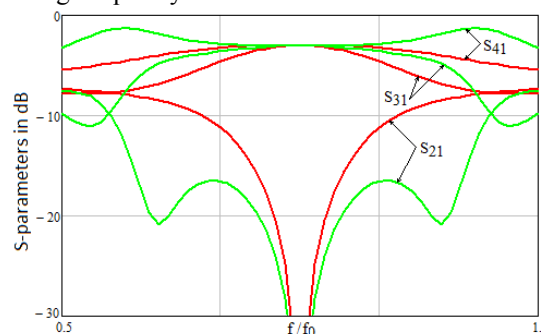

Figure 3 – Frequency dependence of scattering parameters of two-branch (red line) and four-branch (green line) quadrature hybrids

It can be seen from Fig. 3, when the number of branches is increased the operating bandwidth of the coupler is expanded but the longitudinal dimensions of the device are increased significantly in this case.

1 PROBLEM STATEMENT

As mentioned above, the main disadvantages of traditional microstrip couplers are large size and technological limitations when using substrates with $\varepsilon_r \approx 10$. Table 1 shows the parameters of traditional 3- and 4-branch microstrip couplers, which is non-technological (Z_1 for 3-branch and Z_1 and Z_2 for 4-branch) and at the same time, the longitudinal dimensions of these couplers are large enough ($\lambda_2/2$ for 3-branch and $3\lambda_2/4$ for 4-branch couplers).

Table 1 – Non-technological parameters Z_1 and Z_2

Coupler	k	Z_1, Ohm	Z_2, Ohm	Z_3, Ohm	Z_4, Ohm
3-branch	1	120.711	35.355	35.355	–
	1	120.711	50	70.711	–
3-branch	2	157.313	35.355	43.301	–
	2	157.313	50	86.603	–
4-branch	2	150	130	33.29	24.38

In this regard the task of the primary importance is the development of a new structures of small directional couplers with sufficiently wide bandwidth and without technological restrictions in the manufacturing process on dielectric substrates with a large value of ε_r. This problem can be successfully solved by using the idea of combining different types of transmission lines.

2 REVIEW OF THE LITERATURE

In the literature at the miniaturization of microwave devices focus is on the development of new element base based on the traditional planar structures. So in [3] for the reduction in the size of microwave devices is proposed to use buried microstrip lines, which have better electrodynamic parameters as compared to conventional microstrip lines. The works [4, 5, 6] are dedicated to the use of air-gap transmission lines for millimeter-wave applications. Various variants of microstrip lines with inclusions of SRR-structures (split-ring resonators) to reduce the size and improve the electrical characteristics of microwave devices are discussed in [7, 8, 9]. Several examples of using combinations of different planar type transmission lines to create directional couplers are given in [10]. A wide review of the use of known types of planar structures for miniaturization of microwave and millimeter-wave integrated circuits is presented in [11, 12] where it is noted that further progress in this area should be associated with the transition to the three-dimensional structures.

3 MATERIALS AND METHODS

The first conceptual design of a compact coupler on a combination of microstrip and slot line is shown in Fig. 4 a where the top plane is the topology of stripline structure and the lower plane is the topology of slotline structure. Numbers 1, 2, 3, 4 correspond to the numbers of ports of the device and Z_1, Z_2, Z_3 are the impedances of corresponding lines. The equivalent scheme of the coupler is shown in Fig. 4 b).
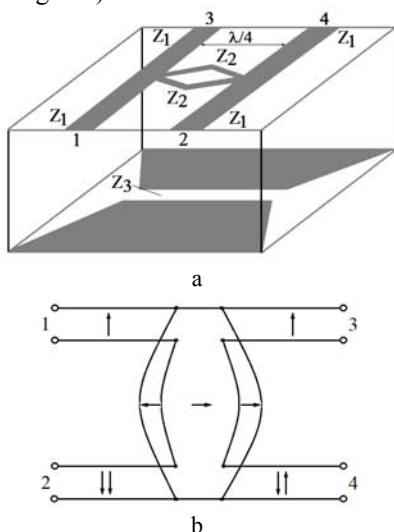

a

b

Figure 4 – Topology a) and equivalent scheme b) of the coupler on the combination of microstrip and slot lines. Arrows on the equivalent scheme show electric field directions in the lines

The scattering matrix of such coupler using even-odd mode decomposition technique and a symmetry of the scheme can be written in the general case as

$$S = \frac{1}{F^2 + G^2} \begin{vmatrix} EG & -jEF & FH & jGH \\ -jEF & EG & jGH & FH \\ FH & jGH & EG & -jEF \\ jGH & FH & -jEF & EG \end{vmatrix}, \qquad (5)$$

where $E = Z_2^2 Z_3 + 2Z_1^2 Z_2 + Z_1^2 Z_3$; $H = 2Z_1 Z_2^2$;

$F = 2Z_1 Z_2 (Z_2 + Z_3)$ $G = Z_2^2 Z_3 - 2Z_1^2 Z_2 - Z_1^2 Z_3$.

It can be seen from Fig. 4 b) that this scheme of coupler is anti-directional; in this design working ports are 2 and 3 and port 4 is isolated. Accordingly the power division ratio will be determined by the expression

$$k = \frac{|S_{21}|^2}{|S_{31}|^2}. \qquad (6)$$

If the conditions of matching and decoupling are fulfilled ($S_{ii} = S_{41} = 0$) then matrix (5) can be simplified and takes the form

$$S = \frac{1}{F^2} \begin{vmatrix} 0 & -jEF & FH & 0 \\ -jEF & 0 & 0 & FH \\ FH & 0 & 0 & -jEF \\ 0 & FH & -jEF & 0 \end{vmatrix}, \qquad (7)$$

from which using (6) it is easy to obtain unambiguous relations for calculating the impedances Z_2 and Z_3 from Z_1 and k:

$$Z_2 = Z_1 \cdot \frac{1 + \sqrt{1+k}}{\sqrt{k}}, \quad Z_3 = Z_1 \cdot \sqrt{k}, \qquad (8)$$

Another design of a compact coupler on the combination of microstrip and slot line is shown in Fig.5. The notation here is same as in Fig. 4.
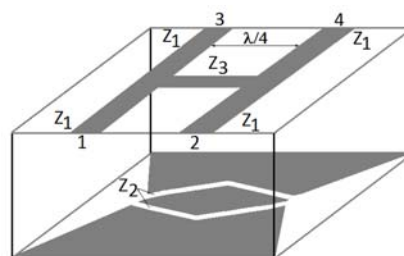

Figure 5 – Another proposed coupler topology based on the combination of microstrip and slot lines

Analogously to the structure shown in Fig. 4, the general form of the scattering matrix of this coupler is of the form:

$$S = \frac{1}{F^2 + G^2} \begin{vmatrix} -jEG & -EF & FH & jGH \\ -EF & -jEG & jGH & FH \\ FH & jGH & -jEG & -EF \\ jGH & FH & -EF & -jEG \end{vmatrix}, \qquad (9)$$

where $E = Z_1^2 + Z_2^2 + 2Z_2Z_3$; $H = 2Z_1Z_3$;

$F = 2Z_1(Z_2 + Z_3)$; $G = -Z_1^2 + Z_2^2 + 2Z_2Z_3$.

Under conditions of full matching and decoupling matrix (9) can be simplified:

$$S = \frac{1}{F^2} \begin{vmatrix} 0 & -EF & FH & 0 \\ -EF & 0 & 0 & FH \\ FH & 0 & 0 & -EF \\ 0 & FH & -EF & 0 \end{vmatrix}, \qquad (10)$$

from which simple formulae to calculate the impedances Z_2 and Z_3 are obtained:

$$Z_2 = Z_1 \cdot \frac{\sqrt{1+k}-1}{\sqrt{k}}, \quad Z_3 = \frac{Z_1}{\sqrt{k}}. \qquad (11)$$

Calculated frequency dependences of scattering parameters for both of the proposed combined microstrip/slot line coupler designs are shown in Fig. 6 (red and green lines). The calculation assumes no dispersion, no losses in the lines, and equal division of power between the output ports. For comparison, the isolation of a classic variant of the three-branch microstrip line hybrid bridge is shown in the same figure (blue curve).

Fig. 6 shows that in the operating band both schemes of couplers have nearly identical characteristics. Importantly, it is apparent from comparison of the curves, both of the proposed designs have better isolation (comparison of red, green and blue line in Fig. 6) as compared to the conventional three-branch hybrid bridge built on a microstrip lines.
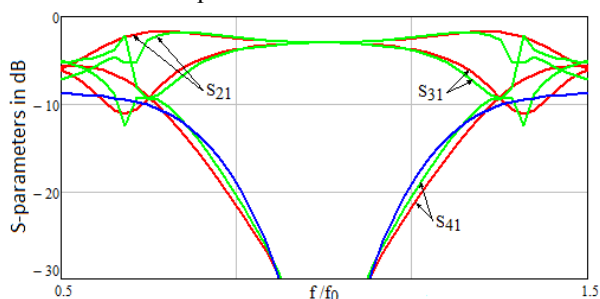
Figure 6 – Frequency dependence of the scattering parameters of the couplers built on a combination of microstrip and slot lines: design from Fig. 4 – red line, design from Fig. 5 – green line, the three-branch microstrip line hybrid bridge – blue line

4 EXPERIMENTS

The simplest variant of topology of proposed directional coupler on combinations of strip and slot transmission lines, corresponding to Fig. 4, is represented on Fig. 7 where Fig. 7 a) shows the topology of microstrip structure and Fig. 7 b) the topology of slotline structure.

AWR Design Environment (MWO) was used to model this structure with the dispersion and losses in the lines. On the figures also shown the decomposition of microstrip and slot line structures to reach good accuracy of calculations.
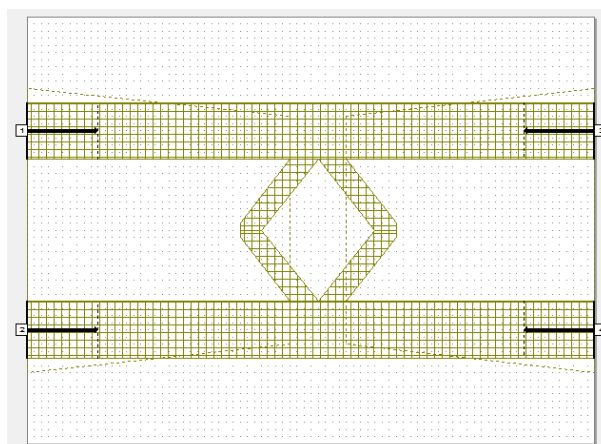
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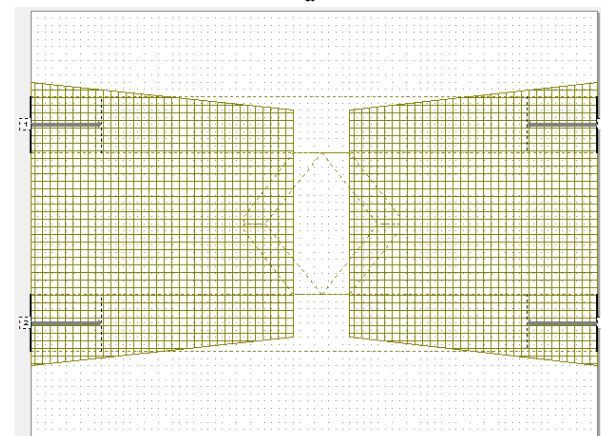
b

Figure 7 – Topology of layers in the MWO: a) stripline and b) slotline structures

It should be noted, that the characteristics of proposed structure is rather sensitive to varying the topology. For example, small modification of coupler slotline structure (with the same stripline structure) as shown in Fig. 8 can significantly change the frequency characteristics of the circuit.
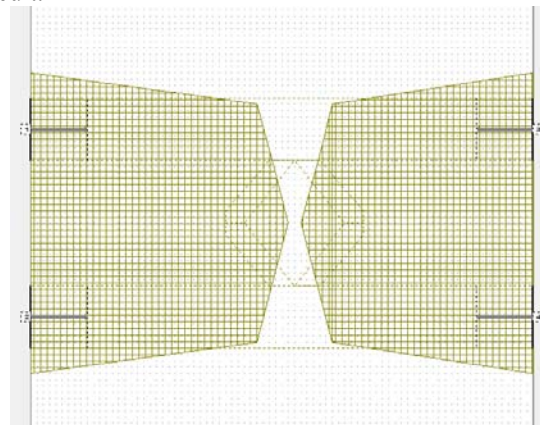
Figure 8 – Modification of the coupler slotline structure

5 RESULTS

Electrodynamic simulation was performed in the frequency range 12–16 GHz using a dielectric GaAs substrate of thickness $h = 1$ mm and parameters $\varepsilon_r = 9.8$ and $\mathrm{tg}\delta = 0.0005$. Simulation results of the coupler with the power division ratio in working arms k=5 are shown in Fig. 9. Under these conditions, the geometric dimensions of the structure were as follows: microstrips (Z_1=50 Ω) W_1=1.037 mm, (Z_2=77.133 Ω) W_2=0.354 mm, slot line (Z_3=111.803 Ω) W_3=0.637 mm.
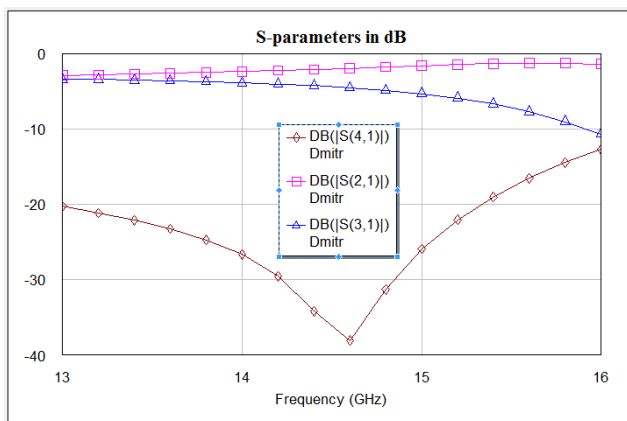

Figure 9 – The frequency characteristics of the directional coupler in the MWO

As noted above the proposed method of designing multilayer structures on combinations of transmission lines has a very great potential in the selection of the required electrical performance of the devices. For example in the case under consideration changing coupler slotline structure as shown in Fig. 8 significantly improve the frequency characteristics of the circuit that is shown in Fig. 10.
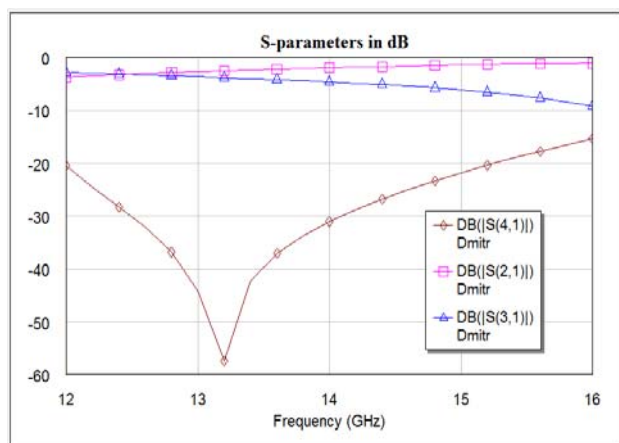

Figure 10 – Characteristics for modified slotline structure

As one can see such simple modification of slotline structure leads to a significantly (about 20 dB) improved isolation (S41) at the operating frequency as compared with the previous version of structure. It also expands the working frequency band of the circuit and improves matching across it that is shown on Fig. 11 where it is

seen VSWR < 2 over the entire frequency range with the minimum value of VSWR = 1.04 at the operating frequency, which demonstrates excellent matching of scheme with the line having characteristic impedance of 50 Ohms.
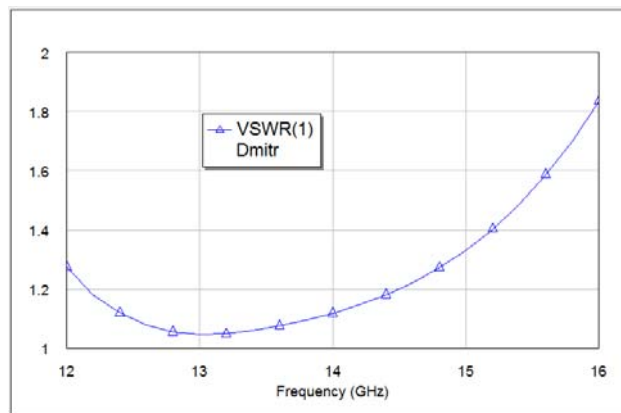

Figure 11 – Frequency dependence of VSWR of the coupler in the frequency range

6 DISCUSSION

In this paper the method of transition from planar to three-dimensional structures and based on this idea develop the designs of directional couplers on combinations of transmission lines is presented. In particular, two variants of compact 3D couplers on combination of microstrip and slot lines are presented. Using the even- and odd-mode excitation and the symmetry of schemes the scattering matrices of couplers are obtained for general case. From the conditions of full matching and isolation, simple formulae are obtained for calculating impedances of $\lambda/4$ transmission line segments that define the topology of the couplers. These formulae are convenient for engineering calculations and allow rapid analysis of schemes with the help of existing automated systems.

It should be noted that in work [10] several variants of structures of directional couplers on combinations of transmission lines are considered, however, there are no results of theoretical analysis, numerical simulation or experiment. In other literary sources, the authors did not find analogues of similar structures. Thus, the directional couplers considered in this paper are proposed for the first time and their characteristics are described in detail analytically and verified by numerical simulation.

The proposed method of designing multilayer structures on combinations of transmission lines has a very great potential in the selection of the required electrical performance of the devices.

CONCLUSIONS

The proposed directional couplers are small in size but have better frequency characteristics than a classic three-branch coupler on microstrip lines. Detailed electrodynamic modeling with the dispersion and losses in the lines confirms the characteristics of proposed

directional couplers. The presented compact coupler designs can find a broad range of applications in mobile communication systems for decoupling of channels, division of power and frequency conversion provided that output ports are not required to be adjacent.

The method of transition from planar to three-dimensional structures used in the paper and in particular the development of directional couplers on combinations of transmission lines permits not only to create compact devices with desired characteristics but also paves the way for significant decrease in the size and costs of the broad range of electronic equipment utilizing such couplers.

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УДК 621.372.83

КОМПАКТНІ СПРЯМОВАНІ ВІДГАЛУЖУВАЧІ З ВИКОРИСТАННЯМ КОМБІНАЦІЇ МІКРОСМУЖКОВИХ І ЩІЛИННИХ ЛІНІЙ

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АНОТАЦІЯ

Актуальність. Перехід сучасної електроніки на більш високі частоти безпосередньо пов'язаний з надзвичайно важливою проблемою мініатюризації інтегральних схем НВЧ. Традиційні плоскі структури, такі як мікросмужкові спрямовані відгалужувачі, мають особливість – їх лінійні розміри визначаються довжиною хвилі в лініях передачі, тому використання таких структур для мініатюризації інтегральних схем НВЧ стає проблематичним.

Мета. Використання 3D-структур на комбінаціях ліній передачі для вивчення частотних властивостей двох можливих реалізацій чвертьхвильових спрямованих відгалужувачі на комбінації мікросмужкових і щілинних ліній передачі. Отримання простих аналітичних виразів для розрахунку електрофізичних параметрів цих спрямованих відгалужувачів і підтвердження їх властивостей суворим електродинамічним розрахунком.

Методи. Метод синфазного і протифазного збудження і теорія матриць розсіювання були використані для отримання простих аналітичних формул для розрахунку імпедансів сегментів ліній передачі, які визначають топологію розглянутих відгалужувачів.

Результати. Електродинамічне моделювання пропонованих відгалужувачів з дисперсією і втратами в лініях показало, що пропоновані конструкції мають кращі частотні характеристики в порівнянні з традиційними трехшлейфними мікросмужковимі спрямованимі відгалужувачами. Також показано, що розглянуті конструкції відгалужувачів мають великий потенціал у виборі необхідних електричних характеристик пристроїв.

Висновки. Представлені компактні відгалужувачі можуть знайти широке застосування в системах мобільного зв'язку для розв'язки каналів, поділу потужності і перетворення частоти. Метод переходу від плоских до тривимірних структур, використовуваний при розробці спрямованих відгалужувачів на комбінаціях ліній передачі, дозволяє не тільки створювати

компактні пристрої з заданими характеристиками, але і відкриває шлях до значного зменшення розмірів і ціни широкого спектру електронного обладнання, що використовує такі відгалужувачі.

КЛЮЧОВІ СЛОВА: Спрямований відгалужувач, мікросмужкова і щілинна лінії, інтегральна схема НВЧ.

КОМПАКТНЫЕ НАПРАВЛЕННЫЕ ОТВЕТВИТЕЛИ С ИСПОЛЬЗОВАНИЕМ КОМБИНАЦИИ МИКРОПОЛОСКОВЫХ И ЩЕЛЕВЫХ ЛИНИЙ

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АННОТАЦИЯ

Актуальность. Переход современной электроники на более высокие частоты напрямую связан с чрезвычайно важной проблемой миниатюризации интегральных схем СВЧ. Традиционные плоские структуры, такие как микрополосковые направленные ответвители, имеют особенность – их линейные размеры определяются длиной волны в линиях передачи, поэтому использование таких структур для миниатюризации интегральных схем СВЧ становится проблематичным.

Цель. Использование 3D-структур на комбинациях линий передачи для изучения частотных свойств двух возможных реализаций четвертьволновых направленных ответвителей на комбинации микрополосковых и щелевых линий передачи. Получение простых аналитических выражений для расчета электрофизических параметров этих направленных ответвителей и подтверждение их свойства строгим электродинамическим расчетом.

Методы. Метод синфазного и противофазного возбуждения и теория матриц рассеяния были использованы для получения простых аналитических формул для расчета импедансов сегментов линий передачи, которые определяют топологию рассматриваемых ответвителей.

Результаты. Электродинамическое моделирование предлагаемых ответвителей с дисперсией и потерями в линиях показало, что предлагаемые конструкции имеют лучшие частотные характеристики по сравнению с традиционными трехшлейфными микрополосковыми направленными ответвителями. Также показано, что рассмотренные конструкции ответвителей имеют большой потенциал в выборе требуемых электрических характеристик устройств.

Выводы. Представленные компактные ответвители могут найти широкое применение в системах мобильной связи для развязки каналов, разделения мощности и преобразования частоты. Метод перехода от плоских к трехмерным структурам, используемый при разработке направленных ответвителей на комбинациях линий передачи, позволяет не только создавать компактные устройства с заданными характеристиками, но и открывает путь к значительному уменьшению размеров и цены широкого спектра электронного оборудования, использующего такие ответвители.

КЛЮЧЕВЫЕ СЛОВА: направленный ответвитель, микрополосковая и щелевая линии, интегральная схема СВЧ.

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