Original scientific paper

Compact Two-position Phase Shifter

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***Abstract* — The paper proposes and investigates the topology of a phase shifter based on a directional coupler. The dimensions of such a device are reduced by using artificial transmission lines instead of quarter-wave sections. By connecting several pairs of phase-shifting cells instead of the usual one, it was possible to obtain a phase shifter design with two phase shifts (instead of one).**

***Keywords* — Slot, miniaturization, stub, coupler.**

I. INTRODUCTION

DIRECTIONAL couplers are widely used in microwave technology, but quadrature directional couplers are the most popular. The classical topology of such a device is represented by two pairs of quarter-wave microstrip line, combined in the form of a square. Such a coupler can perform both power division with a phase difference of 90 degrees, and the summation of power from two signal sources. The couplers are used in the Butler and Blass matrix circuits, in mixers, phase shifters, and more. A phase shifter is a device whose main task is to change the phase by a fixed value. To date, the literature has presented a wide variety of design solutions for the implementation of phase shifters, depending on the specific task of their application. A phase shifter based on a directional coupler consists of an input and output transmission line connected to a coupler, and phase-shifting cells are connected to the remaining two ports through p-i-n diodes. In this regard, the phase shifter and its power circuit will be related to the operating frequency at which they operate. The lower this frequency, the larger the area on the substrate will be occupied by the phase shifter. Since few people are interested in one phase shifter, they are assembled into blocks that provide a phase change with a desired step. Since the main part of the phase shifter is a directional coupler, which divides the input power between its two outputs, and then sums the reflected signals from the two outputs on the remaining output. Therefore, compact directional coupler designs should be considered [1] - [10]. In [1], miniaturization is achieved by adding idle stubs, in [2], the branching of π-form transmission lines made it possible to reduce the size of a power divider operating at two different frequencies, in [3], [5], [10], replacing quarter-wave sections with artificial lines from high-resistance lines and stubs made it possible to obtain a compact coupler, in [4], [6], [9] defects in the screen are used, in [7], low-pass filters are used to miniaturize the coupler, in [8] to miniaturize the separator, bends of lines into the internal space of the device are used. Of course, a phase shifter on a directional coupler is not the only circuit solution for the implementation of phase shifters on a microwave substrate, so let's consider the designs of compact phase shifters, the description of which is presented in the IEEE database. A phase shifter based on a directional coupler with an adjustable phase at the output of the device due to the fact that one pair of quarter-wave segments has a variable length due to the installed inductor-varactor [11]. A compact wideband phase shifter using a microstrip self-coupled line and a broadside-coupled microstrip structure is proposed for a multiphase feed-network [12]. In [13], a design of a phase shifter is proposed, consisting of four microstrip lines of the same length arranged along a circle and connected to each other through diodes (due to a change in length, the output phase changes). The phase shifter whose delay lines are implemented using the Hilbert fractal line is described in [14]. In [15], the design of a modified Schiffman phase shifter is presented, which is capable of providing a smooth phase change at the output due to a change in the voltage on the diode. A tunable phase shifter based on liquid crystals for low-power microwave applications is presented in [16]. A varactor diode based microstrip phase shifter is described in [17]. In [18] the design of the phase shifter with the use of magnetodielectric materials is described. A microstrip phase shifter using right-hand and left-hand segments is presented in [19], using metamaterials and printed transmission lines [20]. In [21], the design of a phase shifter is described, in which the phase change at the output is carried out by switching pin diodes, due to which segments of different physical lengths are connected. In our work, we investigated the designs of phase shifters in which several phase-shifting lines are connected, which makes it possible to obtain several phase changes in one device [22]. Such a schematic and constructive solution can significantly reduce the area of the phase shifter unit. The design of such devices and the analysis of the obtained characteristics were carried out in Cadence AWR. The proposed phase shifter is quite difficult to compare with those considered, since they have different circuitry implementation on the printed circuit board. However, for the proposed phase shifter, one can single out the simplicity of its implementation, since it includes a well-known directional coupler, and the described technique for designing a phase shifter with reduced dimensions quite easily allows you to calculate the topology of the device.

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II. PHASER SHIFTER

A reflective type phase shifter based on a directional coupler is shown in Fig. 1. The principle of operation of such a phase shifter is that phase-shifting cells (usually stubs) are connected to two outputs of the device through pin diodes, which, depending on the state of the diodes, are connected or disconnected and thus this changes the phase at the output of the phase shifter. The magnitude of this phase depends on the electrical lengths of the phase-shifting cells. In our design, open circuits stubs are used, so their length should be two times shorter such as the signal travels twice the distance. In the design of the phase shifter there are several areas of the power supply circuit (1) consisting of high-resistance and low-resistance segments acting as inductors and capacitance; phase-shifting segments (2), providing the desired phase shift when connecting diodes that are installed in the gaps between the lines (4); directional coupler (3), performing the division and summation of the microwave signals; framed quarter-wave microstrip segment (5), to provide a return current.

For an example of our design, a frequency of 1.5 GHz was taken (if necessary, this phase shifter can be calculated for a different operating frequency and a substrate with other parameters can be used). In our case, we took an affordable and widely known FR4 material with a thickness of 1 mm. The theoretical characteristics were calculated using AVR; they are shown in Fig. 2. The purpose of this work is to obtain a phase shifter design whose dimensions are significantly smaller than its standard implementation and provides several phase shifts, which allows significant savings on the cost of the prototype. The area of the coupler shown in the figure is 965.5 mm^2.

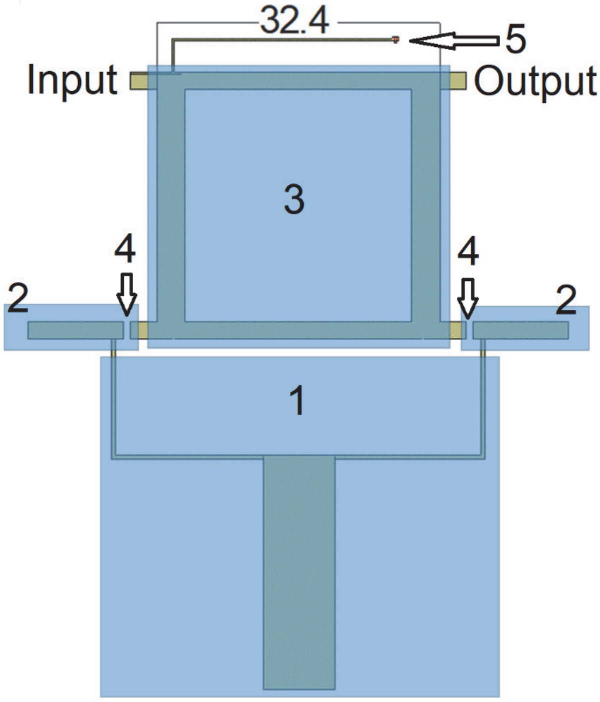

Fig. 1. Phase shifter standard layout.

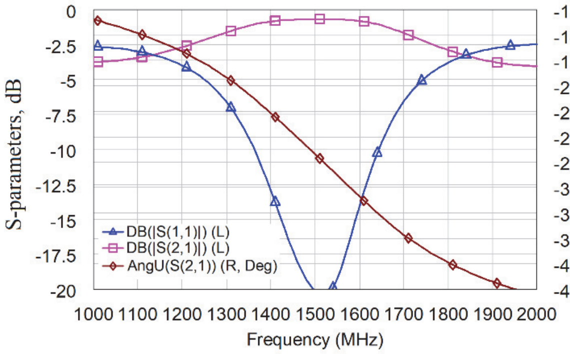

Fig. 2. Graph of S-parameters from the frequency of the phase shifter (diodes are disabled).

According to the obtained frequency dependences, such parameters of the coupler were determined as the operating frequency band (estimated by the isolation level of 15 dB) is equal to 1450 MHz. An imbalance between gains of ±0.5 dB remains in the 740 MHz frequency band. The phase shifter operates at a center frequency of 1.5 GHz. With the p-i-n diodes off, the coefficient of the scattering matrix S_{21} is at 0.7 dB. As can be seen in Fig. 1, the topology of the phase shifter has significant dimensions: a coupler in the classical design has a large area and an area that is not used in any way, enclosed within quarter-wave segments; a significant area is occupied by the power supply circuit for pin diodes. Therefore, in order to reduce the dimensions of the phase shifter, instead of the classic coupler, its miniature implementation is installed, made on artificial transmission lines. An artificial transmission line consists of high-resistance sections (inductances) and idle loops (capacitors). Artificial transmission lines can be represented as matching circuits, which can be implemented in the form of Г, T and П-shaped circuits (Fig. 3). These lines are installed instead of the classic quarter-wave segments.

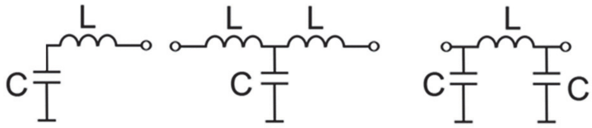

Fig. 3. Г-, T- and П-shaped matching circuits.

The simplest is the Г-scheme. However, such a scheme performs matching only in one direction, which is not suitable for use in couplers designs that are reciprocal devices. T and П-shaped circuits represent the connection of two L-shaped circuits and they can be calculated using the formulas presented in [23]. It is also possible to calculate T- and П-schemes by using their ABCD matrices (transfer matrices [A]) and the following formulas:

$$\cos\varphi = \frac{A+D}{2} \tag{1}$$

$$\rho = \sqrt{\frac{L}{C}} \tag{2}$$

where A and D are the elements of the ABCD matrix.

Formula (1) allows you to calculate the phase shift of T and П-shaped circuits, and formula (2), knowing the wave impedance of the microstrip line segment and choosing the nominal inductance or capacitance, allows you to determine the value of the remaining element [24].

Also, the denominations of the necessary elements can be calculated using formulas that can be obtained from the formulas of long lines:

$$L_T = \frac{\rho}{\omega} tg \frac{\theta}{2} \tag{3}$$

$$C_T = \frac{1}{\omega\rho} \sin\theta \tag{4}$$

where $\omega_0 = 2\pi f_0$, f_0 is the central frequency of the device.

A short length of high impedance transmission line will be equivalent to series inductance. Conversely, if a segment has a low characteristic impedance, then it is equivalent to a parallel capacitance. The idle train will behave differently depending on the length. At less than a quarter wavelength, it will be equivalent to capacitance, and at more than a quarter wavelength, it will be equivalent to inductance. This can be determined based on the input resistance of the stub (5), where Z_L - load resistance. Based on the input resistance formula, formulas were obtained to determine the input resistances of short circuit (SC) and open circuit (OC) stubs (6) - (7). Graphs of input resistances for short-circuit and open-circuit stubs are shown in Fig. 4, 5.

$$Z_{in} = \rho \frac{Z_L + j\rho tg \beta l}{\rho + jZ_L tg \beta l} \tag{5}$$

$$Z_{in}^{oc} = -j\rho ctg(\beta l) \tag{6}$$

$$Z_{in}^{sc} = j\rho tg(\beta l) \tag{7}$$

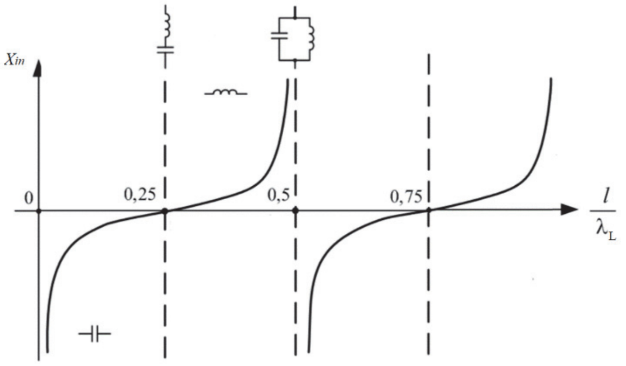

Fig. 4. Open-circuit stub input resistance graph.

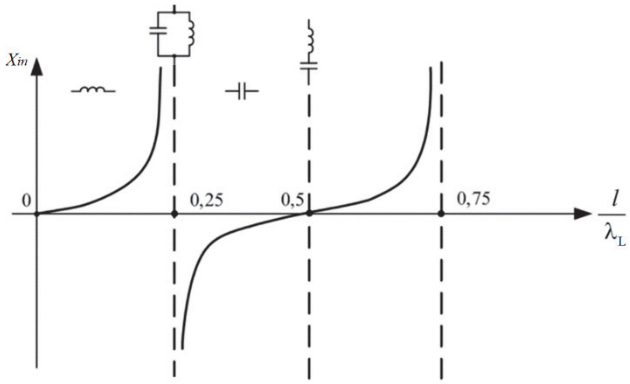

Fig. 5. Short-circuit stub input resistance graph.

The capacity of the idle stubs is calculated using the following formula:

$$C = \frac{l}{\rho f \lambda_L} \tag{8}$$

$$\lambda_L = \frac{\lambda_0}{\sqrt{\varepsilon_{эф}}} \tag{9}$$

where $\lambda_0 = c/f$ is the wavelength; c is the speed of light.

The compact phase shifter is shown in Fig. 5, and its characteristics in Fig. 6. It can be seen that the area of the coupler has been significantly reduced, (Fig. 5) the area has decreased by 74.5% (246.5 mm^2), relative to the full-size design. Such a phase shifter operates at a frequency of 1.5 GHz, the transmission coefficient with the p-i-n diodes turned off is 1.9 dB. Also, for a greater degree of miniaturization (reducing the dimensions of the phase shifter relative to its classical implementation), the usual phase-shifting cells in the form of microstrip lines have also been replaced with artificial transmission lines.

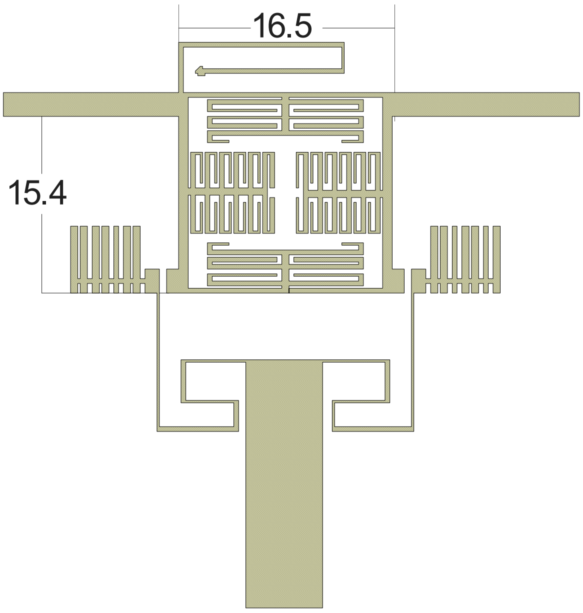

Fig. 5. Phase shifter compact layout with curved stubs.

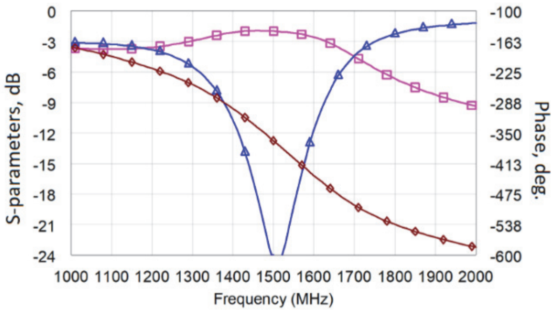

Fig. 6. Graph of S-parameters from the frequency of the phase shifter (diodes are disabled).

As shown in Fig. 5, the phase shifter with curved stubs operates at a frequency of 1.5 GHz, the transmission coefficient with the p-i-n diodes turned off is 1.7 dB. In general, it can be seen that the phase shifter has small dimensions and similar characteristics to the classical design. However, the diode power supply circuit still occupies a significant area on the printed circuit board. Therefore, the easiest way to reduce its size is to replace the distributed elements with concentrated ones. It is also worth noting that if it is necessary to obtain two phase shifts at the output of the phase shifter, it will be necessary to connect two phase shifters with different phase-shifting cells (on their own phase shift), which will lead to an increase in the dimensions of the device. Therefore, in order to get another phase shift at the output of the device, it is necessary to add another pair of contact diodes and phase-shifting cells. Fig. 7 shows the design of such a phase shifter, and Fig. 8, 9 shows the frequency characteristics.

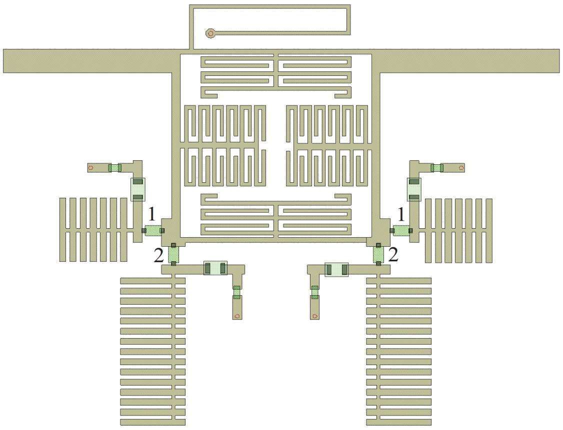

Fig. 7. Topology of a compact directional coupler.

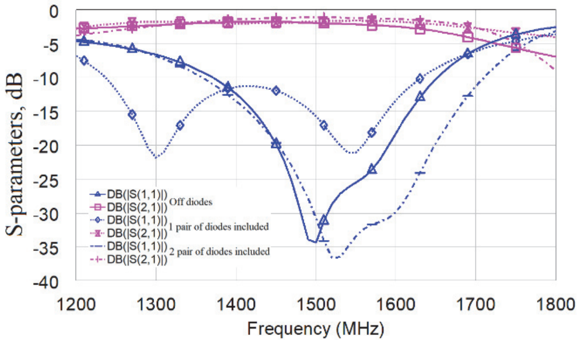

Fig. 8. Graph of S-parameters from the frequency of the coupler.

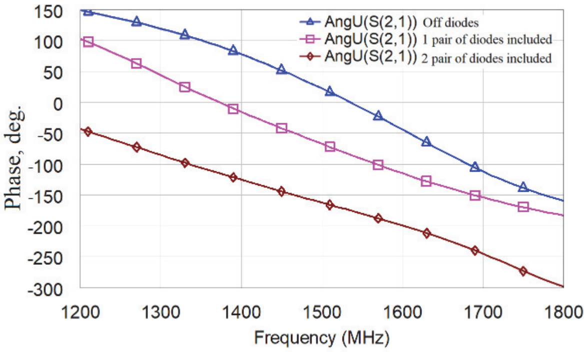

Fig. 9. Graph of the phase difference of the output signals of the coupler.

In addition to the design of the phase shifter (Fig. 7), one more pair of phase-shifting segments can be connected, which will make it possible to obtain a three-position phase shifter. However, the addition of another pair of phase-shifting cells will complicate the design of the phase shifter, but if necessary and with due attention during design, such a structure can be designed and a prototype can be made. The amount of phase change at the output of the device depends on the type of stubs and their length. The proposed circuit design solution allows to reduce the size of the phase shifter due to the use of artificial transmission lines and the implementation of the power circuit in the form of lumped elements. However, the use of several phase-shifting segments makes it possible to replace several phase shifters with one.

It is worth highlighting a general algorithm of actions that will allow any reader to repeat my calculations:

1. It is necessary to calculate the classical design of the phase shifter and verify its operability. Then it is necessary to evaluate the frequency characteristics of this device. All this information will allow you to evaluate the performance of a miniature phase shifter - its dimensions and losses in characteristics (loss growth, narrowing of the operating frequency band, and more).
2. Calculate artificial transmission lines using formulas that allow you to determine the nominal values of the elements (inductors and capacitances). Using well-known formulas, it is possible to calculate the topology of elements that would provide similar nominal values on a printed circuit board.
3. Perform a reverse transition from distributed elements to concentrated ones, which will reduce the area occupied by the diode power circuits.
4. Perform the calculation of the resulting design of the phase shifter to check its operability. If necessary, adjust the dimensions of the elements (if the operating frequency has deviated to the upper side, then it is necessary to increase the dimensions of the elements, and vice versa if the frequency has deviated to the lower side).

It should also be noted that the process of miniaturization of the phase shifter should be started separately with a directional coupler. After the design of the miniature coupler is obtained, according to the algorithm described above, it is necessary to proceed to the miniaturization of phase-shifting cells, and then to the reduction of power circuits by switching from distributed elements to concentrated elements. The quarter-wave loop, which provides contact with the screen, should also be bent to reduce the dimensions of the entire device. Such a step-by-step process of designing the device will minimize errors and keep its characteristics under control.

III. CONCLUSION

The design of a compact phase shifter with two variable phase shifts is proposed and investigated. This was achieved through the use of artificial transmission lines, replacement of power circuits with lumped elements and the use of two pairs of phase-shifting cells. Artificial transmission lines, installed instead of quarter-wave sections, made it possible to reduce the size of the coupler. The use of lumped elements instead of distributed ones made it possible to reduce the size of the power circuits. The installation of two pairs of phase-shifting cells as part of the phase shifter made it possible to achieve a phase change by two fixed values.

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