Original scientific paper

Miniaturization of Directional Couplers without the use of Multilayer Substrates by Changing the Design of the Capacitor

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***Abstract* — When the limit miniaturization of the coupler is achieved when the elements are located in one conductive layer, then miniaturization can be continued by changing the design of the capacitor that is part of the filter: reducing the gap between the plates or increasing the dielectric constant between the capacitor plates, and due to the movable plates, you can change the operating frequency of the coupler.**

***Keywords* — plates, permittivity, cutouts in the substrate, miniaturization.**

I. Introduction

MICROSTRIP directional couplers are the basic elements for various radio engineering devices such as phase shifters, combiners, mixers, antenna arrays and beamforming circuits. They distribute the input power equally between the two outputs with a phase difference of 90°. The classic coupler design includes two pairs of quarter-wave lengths of the transmission line, which form a rectangle, one of which has a resistance of 50 ohms, and the other has a resistance of 35 ohms. The dimensions of microstrip directional couplers are related to the length of the transmission lines. In the UHF band, in which devices such as GSM, Wi-Fi, 3G, 4G, GPS, GLONASS and others operate, bridges are of considerable size, and a large area inside the bridge, enclosed between quarter-wave segments, remains unused. Therefore, the UHF band was chosen for the development of compact microstrip directional couplers. Bandwidth narrowing, output gains and phase differences, increased insertion loss, decreased isolation, and increased input reflectance are common problems that arise when downsizing microstrip directional couplers. This emphasizes the relevance of research aimed at developing a methodology for designing compact microstrip directional couplers and devices based on them.

In the literature, most of the work related to the miniaturization of couplers is the replacement of quarter-wave segments with some kind of structure: T-equivalent circuit models [1], compact right-left handed structure based hybrid coupler [2], lumped components instead of transmission lines [3], bends of microstrip segments [4], artificial transmission lines [5], Quasi-Lumped Elements Approach With Nonsymmetrical and Symmetrical T-Shaped Structure [6], lumped-element [7], artificial transmission lines [58], asymmetrical T-structure slow-wave loading [9], patch elements [10], low-pass filter [11, 12, 13], distributed capacitors [14], several original variants of compact couplers [15], changing the design of the capacitor to miniaturize the coupler [16]. The authors of the listed works solve the problems of miniaturization by replacing segments with structures whose elements are located in one or more layers of the substrate.

However, when considering the case when all elements of the device are located in one conductive layer, the area inside the directional coupler is limited. This, in turn, limits the layout of structural elements used for device miniaturization. If the structural elements fully use the available area inside the coupler, then the miniaturization limit of the device is reached. However, little attention is paid to what to do when the area inside the bridge is fully utilized and the maximum possible miniaturization is achieved. Therefore, the purpose of this work is to consider circuit engineering approaches that make it possible to further increase the degree of miniaturization of directional couplers, in which all elements are made in a single conductive layer.

II. The Design Of The Coupler

Miniaturization is one of the important directions in modern radio electronics, aimed at creating devices with significantly reduced overall dimensions and weight. To achieve this goal, new constructive and technological solutions are used based on the use of elements with characteristics equivalent to those of microstrip lines, but with geometry and interelement connections that allow increasing the degree of miniaturization of traditional structures.

In topologies using microstrip lines, segments are replaced by segments of shorter length with conductor topology that differs from the original one and have similar frequency characteristics in the vicinity of the center frequency of the device. These sections are described by the long line model. They are U-(CLC - capacitance, inductance, capacitance) or T-shaped links (LCL - inductance, capacitance, inductance), which are low-pass filters.

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From a miniaturization point of view, the use of T-links is more advantageous than U-links. This is due to the fact that in order to increase the degree of miniaturization when using U-shaped links, it is necessary to combine the capacitive elements of neighboring links, which can complicate the process of tuning the coupler to the desired characteristics. The calculation of the inductances and capacitances that make up the T-link is performed using the following formulas:

$$L_T = \frac{\rho}{\omega} tg \frac{\theta}{2} \quad (1)$$

$$C_T = \frac{1}{\omega\rho} \sin\theta \quad (2)$$

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

To miniaturize the coupler, you can use the technique of replacing segments with links that provide the same phase shifts of signals at the center frequency and in its vicinity, but have a shorter length. To apply the technique, it is necessary to perform the following steps, provided that the center frequency, substrate parameters, and wave impedances (ρ) of the quarter-wave sections (θ=90°) of the coupler are given: calculate the ratings of the LC elements for the required T- or U-shaped links using the formulas; move from calculated lumped LC-elements to elements with distributed parameters; with the help of electrodynamic simulation tools, correct the dimensions of the elements of a compact device to achieve the required characteristics.

A compact coupler with an operating frequency of 1 GHz was developed on an FR4 substrate (ε = 4.4, tanδ = 0.02) using the described technique. The topology of the coupler is shown in Fig. 1, and its calculated frequency characteristics, obtained using Ansys HFSS, are shown in Fig. 2 and 3. The area of the compact coupler is 449.43 mm^2 (0.118λ_l x 0.117λ_l), which is 4.5 times less than that of the classical design (2022 mm^2, 0.25λ_l x 0.25λ_l). The relative range in which the decoupling level is less than 20 dB is 7.5%, in contrast to the classic coupler, which has 10%. At the center frequency, the phase difference of the output signals of the coupler is 90°, and the gain is -3.7 dB (0.5 dB worse than the classic one). Capacitors occupy most of the area of the compact coupler in Fig. 1. If the internal area of the device is fully used, then its further miniaturization is possible by reducing the width of high-resistance segments (increasing the inductance) by the possible value. However, their width is limited by technological capabilities.

Therefore, it is more profitable to reduce the size of the capacitive elements of the T-shaped links, which occupy a large area of the coupler. There are two options for reducing capacitive elements - this is the use of a material between the plates with a higher dielectric constant, which greatly complicates the design of the coupler, or a decrease in the gap between the plates of a plane-parallel capacitor, which is not so difficult to implement in practice.

It should also be noted that with an increase in the degree of miniaturization, there are limitations associated with the manufacturability of the device. The limiting width of microstrip lines and the size of the gap between the conductors is selected taking into account the accuracy class and the available means of technological equipment.

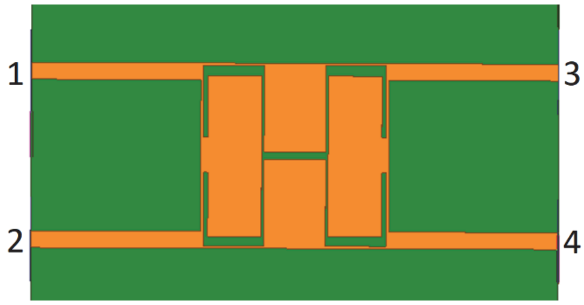

Fig. 1. Layout of a compact coupler implemented on T-circuits.

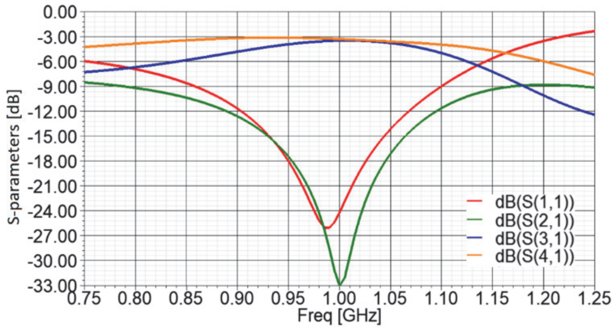

Fig. 2. Graph of the S-parameters of a compact coupler against frequency.

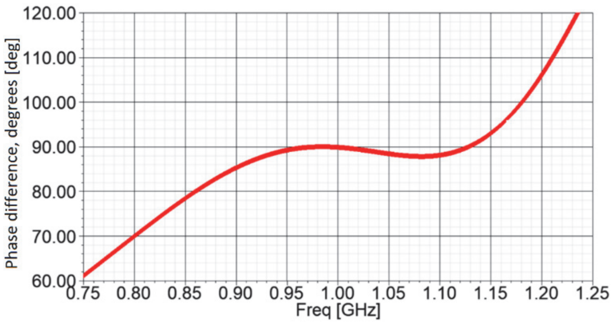

Fig. 3. Graph of the phase difference of the output signals of the coupler from the frequency.

If the FR4 substrate material is replaced by the FLAN-7.2 material with a permittivity ε = 7.2 while maintaining a thickness of 1 mm, then an additional reduction in the coupler dimensions can be achieved. The dimensions of the compact coupler on the FLAN-7.2 substrate are 18 × 18.9 = 340.2 mm^2 (0.1λ_l x 0.105λ_l), which is 24.3% less than that of the coupler in Fig. 1. To check the operation of the coupler on a new substrate, the frequency responses were calculated using the HFSS program, which are shown in Fig. 5 and 6.

When using dielectric inserts and a corresponding change in the design of the coupler, there is some deterioration in its frequency characteristics. At the center frequency of 1 GHz, the phase difference of the output signals of the coupler is 90.5°, and the gains are -3.7 dB. The relative bandwidth of operating frequencies at the level of -20 dB isolation factor is 2%.

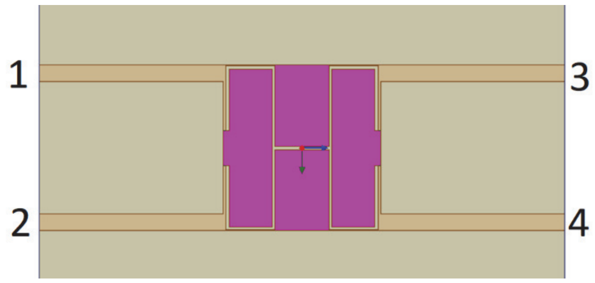

Fig. 4. Layout of a compact coupler implemented on T-circuits with increased dielectric constant of the substrate material.

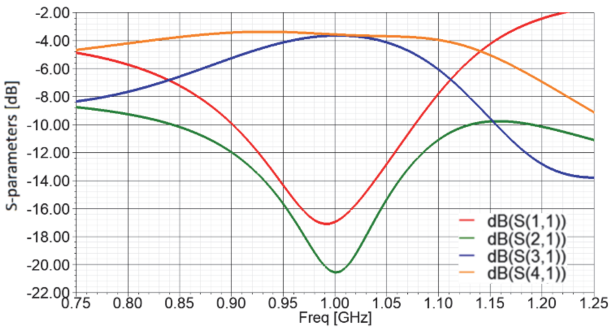

Fig. 5. Graph of the S-parameters of a compact coupler against frequency.

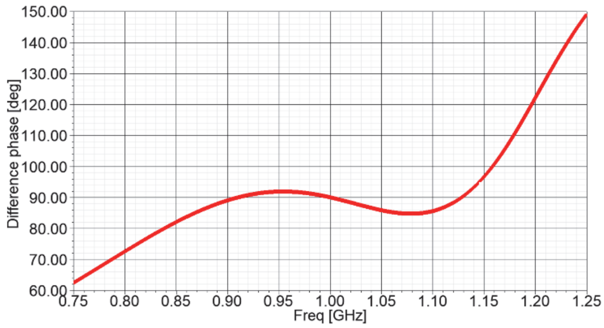

Fig. 6. Graph of the phase difference of the output signals of the coupler from the frequency.

Dielectric inserts in the design of the coupler can be made movable, which will allow you to change the dielectric constant under the capacitive elements. The standard design of a directional coupler is to operate at a specific frequency. To achieve the possibility of changing the operating frequency of the coupler, a variable capacitance included in the low-pass filter can be used. The ratings of such elements can be changed mechanically or electrically. In our work, we present the design of a compact directional coupler, in which the capacitance changes mechanically. Unlike the electronic restructuring of the element ratings, the mechanical method does not require the installation of additional components and power. However, the disadvantage of mechanically retuning a capacitor is the potential inaccuracy in setting the desired value. However, this approach can be applied to study the operation of a compact coupler or to conduct laboratory work.

To change the operating frequency of the coupler to the specified values, you can use sliding plates that allow you to change the values of the capacitors and, accordingly, the operating frequency of the device (Fig. 7). In this case, plates made of different materials or different variations of the same substrate material can be used, and the material can also be either solid or mesh. With an increase in the dielectric constant of the layer between the plates of the capacitor, its value increases, and with a decrease, it decreases. Accordingly, the center frequency of the coupler also changes.

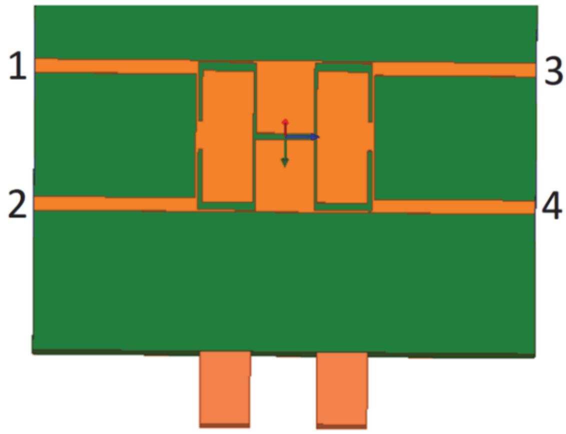

Fig. 7. Topology of a compact coupler with sliding plates.

To shift the center frequency of a compact coupler by specified values down or up by 0.15 GHz, dielectric strips of various thicknesses and permittivity ε can be used. In particular, to shift the frequency down by 0.15 GHz, it is required to use strips with ε = 7 and ε = 6.5 1 mm thick, and to shift the frequency up by 0.15 GHz, it is required to use strips with ε = 2.85 and ε = 2.75 1 mm thick (Fig. 8). The characteristics of couplers with such parameters were calculated using the HFSS program and are presented in Figures 9 and 10.

An analysis of the simulation results shows that the use of different dielectric strips makes it possible to change the operating frequency of a compact coupler by specified values. However, the practical implementation of this approach should take into account the limitations associated with the availability of materials with the required values of the permittivity. Or use mesh inserts in which, due to air inclusions, you can achieve the desired dielectric constant.

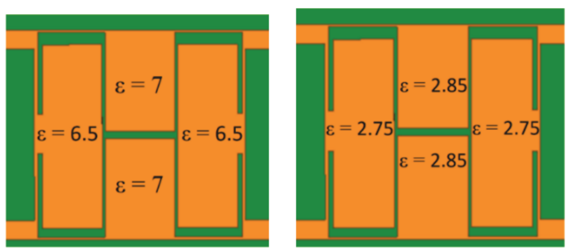

Fig. 8. Values of dielectric constants of layers between capacitor plates: -0.15 GHz (left) and +0.15 GHz (right).

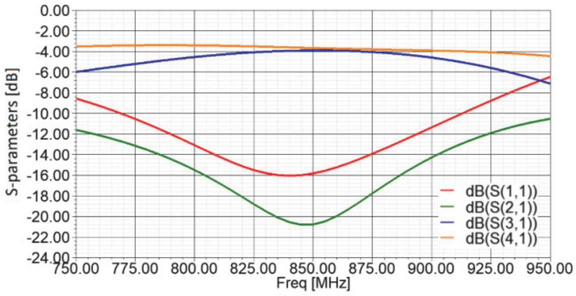

Fig. 9. Compact coupler frequency response (S-parameters and output phase difference) with center frequency shifted down by 0.15 GHz.

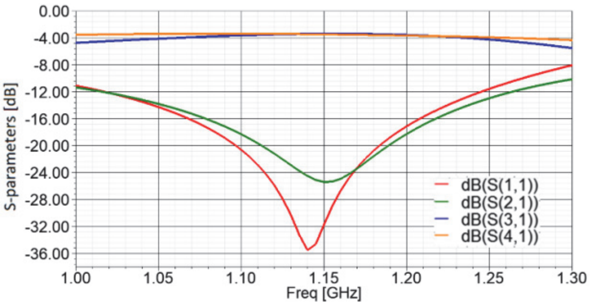

Fig. 10. Compact coupler frequency response (S-parameters and output signal phase difference) with center frequency shifted up by 0.15 GHz.

For further miniaturization of the coupler in Fig. 11, you can reduce the gaps between the capacitor plates. Such a reduction will make it possible to use the freed up internal area of the device for additional miniaturization of the directional coupler.

Fig. 11. Implementation of a plane-parallel capacitor using multilayer technology.

If you reduce the distance between the capacitor plates from 1 mm ($h_1 + h_2$) to 0.8 mm (h_1), then you can reduce the size of the coupler to 20 x 20.1 = 402 mm^2 ($0.111\lambda_l$ x $0.112\lambda_l$), while as a substrate FR4 material is used with parameters: $\varepsilon = 4.4$ and $\tan\delta = 0.02$. The frequency responses of such a device were calculated by numerical simulation and are shown in Figures 12 and 13. The relative operating bandwidth at -20 dB isolation factor is 6.3%. At the center frequency of 1 GHz, the coupler output signals have a phase difference of 90° and a gain of -3.55 dB.

Descriptions of how to increase the miniaturization of a coupler while fully utilizing the internal area of the device. After receiving, a compact directional coupler (in which the quarter-wave segments are replaced by low-pass filters), for example, using photolithography. In places where capacitive elements are installed, the excess substrate is removed from the side of the screen. This makes it possible to reduce the thickness of the substrate under the capacitive elements. In this case, after reducing the thickness of the substrate, a metallization operation is performed to restore electrical contact with the common screen. This approach allows further miniaturization of the coupler, in which the free space is fully used, by reducing the dimensions of the capacitive elements. The special recesses in the screen under the low-pass filter capacitor plates are shown in Figure 10.

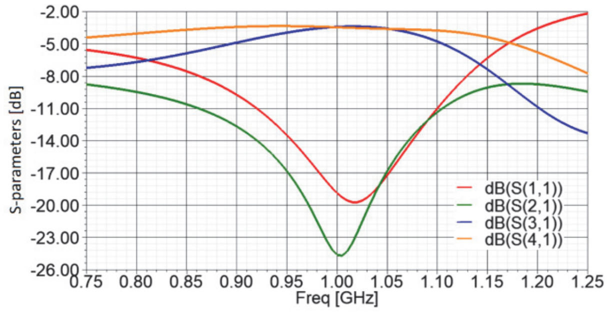

Fig. 12. Graph of the S-parameters of a compact coupler against frequency.

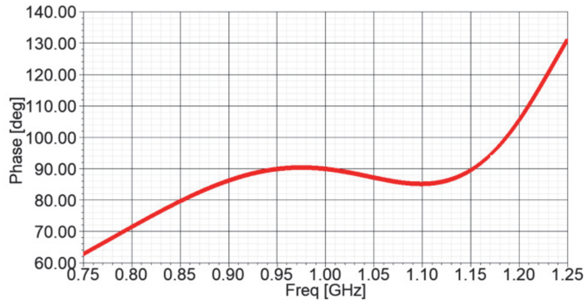

Fig. 13. Graph of the phase difference of the output signals of the coupler from the frequency.

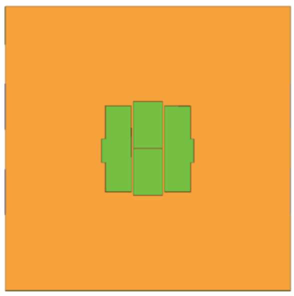

Fig. 14. Recesses in the substrate on the side of the screen under the capacitive elements of the low-pass filters of the compact coupler

In practice, the design of the coupler in Figure 10 can be obtained by milling the substrate under the capacitors in the shield layer and subsequent metallization to restore electrical contact with the shield.

Another implementation option is the use of two microwave substrates, one of which has through holes in the shape of capacitors. These substrates are combined, after which an additional layer of metallization is applied to restore the screen from the underside. The disadvantage of this approach is the need for the formation of cutouts and additional plating. However, at the current level of technological development, this disadvantage is not significant.

The described cutouts under the capacitive elements on the side of the screen make it possible to further increase the degree of miniaturization of the coupler when its elements are implemented in one conductive layer. This approach makes it possible in some cases to avoid the use of multilayer printed circuit boards, which simplifies and reduces the cost of the device design.

III. Conclusion

This paper describes a technique to improve the efficiency of miniaturization of directional couplers using low-pass filters that allow full use of the internal area of the device. This technique can be used to further reduce the area of the device on the board by increasing the dielectric constant or reducing the thickness of the substrate between the plates of capacitors included in T-shaped links. An increase in the permittivity between the capacitor plates made it possible to further reduce the area of the compact coupler by 24.3%, increasing the degree of miniaturization of the coupler from 77.77% to 83.17%. However, this resulted in a -20 dB decoupling bandwidth reduction. The use of a decrease in the gap between the plates of the capacitors of the T-shaped links made it possible to reduce the degree of miniaturization of the coupler to 80.12%. This is not yet the final result, since the gap between the capacitor plates can be further reduced.

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