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Compact directional coupler with five stubs

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Abstract. In this paper, a compact design of a five-stub microstrip 3-dB coupler with significantly reduced overall dimensions has been developed and investigated. To downsize the conventional layout, artificial transmission line segments, whose characteristics are equivalent to quarter-wave segments at the frequency of 2000 MHz and its neighbourhood, were used. This enables to obtain an area of the compact coupler which is 83.15% less than the conventional one, with just 26.15 % reduction in the operating frequency band.

1. Introduction

A branch-line (or 3-dB) coupler is a four-port device designed to divide the power incoming from one port equally between two other ones, whereas the fourth port remains isolated. An interest in miniaturizing the devices of this type is primarily contingent on the tendency to introduce microwave devices in the composition of integrated circuits while maintaining their performance. The design of the five-stub directional coupler is a modified design of a two branch-line coupler, which includes additional quarter-wave stubs in order to increase the operating frequency band. The coupler considered can be used for the division and the summation of power, as well as for feeding antenna systems. Since the conventional five-stub coupler has a quarter-wave width and, a length equal to the wavelength of the transmission line, the lower the operating frequency, the larger the area occupied. Today, there are a large number of possible methods to effectively reduce the dimensions of microstrip devices [1-5]. This work is aimed at miniaturizing a four-port coupler using original microstrip structures, equivalent to quarter-wave segments in a given frequency band [6].

2. Design coupler

The microstrip branch-line couplers used around the world are based on different design solutions. However, the difference generally consists just in the wave impedance values of the quarter-wave segments. The purpose of the present work is to miniaturize the five-stub coupler design so that the characteristics of the device are deteriorated minimally. The development and investigation of the designs are carried out using the NI AWR Design Environment software. The commonly used 1-mm-thick FR-4 substrate with relative permittivity ε_r = 4.4 and loss tangent tanδ = 0.02 was used as material. The block diagram and layout of the conventional design with the calculated impedances are shown in figures 1 and 2, respectively. The results of S-parameters and phase differences are shown in figures 3 and 4, respectively. The occupied area turns out to be 31.6 mm x 80.6 mm = 2547 mm^2.

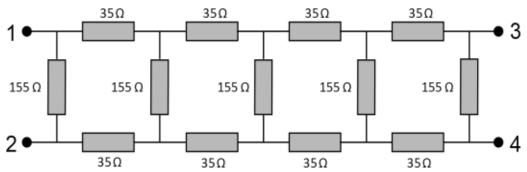

Figure 1. Block-diagram of a five-stub coupler tuned to the frequency of 2000 MHz.

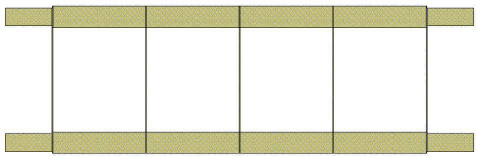

Figure 2. Conventional layout of a five-stub coupler tuned to the frequency of 2000 MHz.

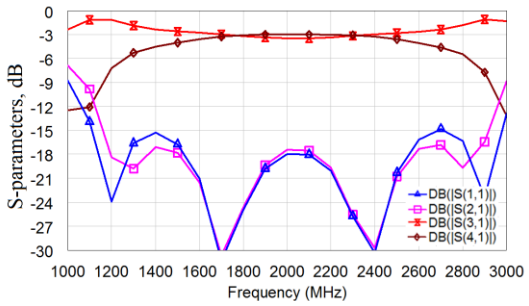

Figure 3. S-parameters of a traditional coupler based on Fig. 1 designed at a centre frequency of 2000 MHz.

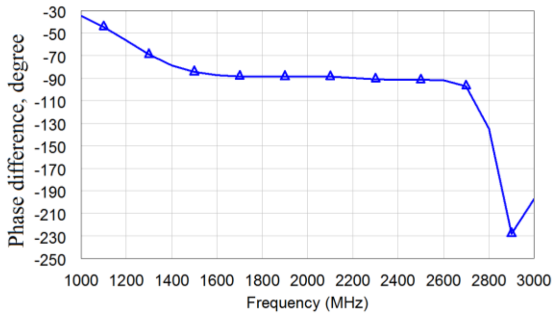

Figure 4. Phase difference between the signals at the coupler outputs for a coupler tuned to the frequency of 2000 MHz.

Based on the calculated frequency characteristics, it is possible to determine that the central frequency of operation is 2000 MHz, and the corresponding phase difference reaches 90 degrees. The frequency band estimated at a decoupling level of –15 dB amounts to 1758 MHz, or 87.9% bandwidth. The S11 parameter does not exceed –15 dB within this whole frequency band. The next step is the development of the electrodynamic structures with a phase shift of 90 degrees at the central frequency. These structures are shorter but wider than the conventional microstrip segments. However, the protruding elements of the newly developed structures are fitted in the free space inside the coupler.

The synthesis of the electrodynamic structures consists in the following steps:

1) Select the resistance value of high-impedance lines (which play the role of inductances), for example 100 Ohm, as well as their length.

2) Determine the capacitance value using the resistance formula. Knowing the values of the inductance and the resistance, it is straightforward to deduce the nominal value of the required capacitance.

3) Recalculate the values of the elements from the equivalent scheme to the parameters of the corresponding microstrip layout.

The simplest way to implement the inductance is to use a long segment of the transmission line. The implementation of the capacitance can be different. It is a low-impedance segment, or open circuit stub, whose length is less than a quarter wavelength. In the present work, we realized the capacitance as an open circuit stub bent in the form of a meander. The gaps between adjacent elements are selected on the basis of the layout technological feasibility. Using the structures suggested we managed to reduce the dimensions of the 3-dB coupler. The electrodynamic structures have the same phase at the central frequency of operation as well in its neighborhood. This makes it possible to obtain the coupler compact design which has characteristics consistent with the performance of the full-sized device. The final version of the compact five-stub coupler is shown in figure 5. The area resulting from optimization turned out to be 13.9 mm x 30.9 mm = 429.5 mm^2. Thus, the area of the compact design is 83.15% less than the area of the conventional coupler. Since it is required to obtain the maximum reduction in dimensions, the number and sizes are selected in such a way as to maximally utilize the space inside the coupler. Because artificial transmission lines are used for the miniaturization, couplers act as low-pass filters, and they provide harmonic suppression in a certain frequency band. The results of S-parameters and phase differences are shown in figures 6 and 7, respectively. The electrical lengths of the conventional and artificial microstrip line segments are compared in figure 8.

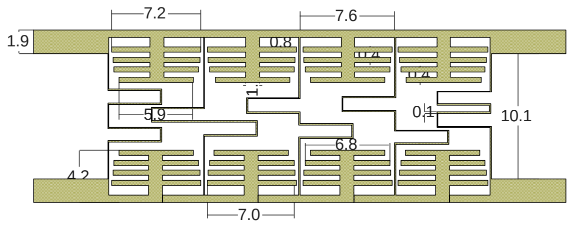

Figure 5. Layout of a compact 3-dB coupler tuned to the frequency of 2000 MHz.

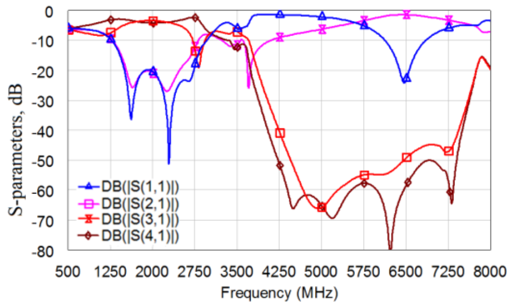

Figure 6. S-parameters of a compact coupler tuned to a centre frequency of 2000 MHz.

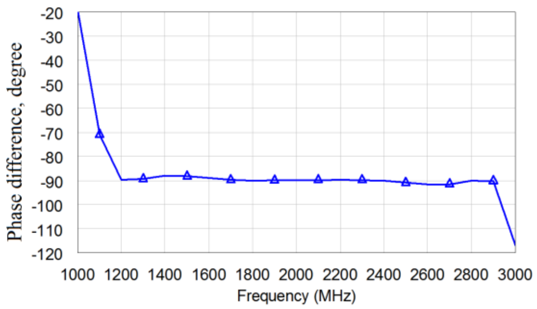

Figure 7. Phase difference between signals at the outputs of the coupler developed.

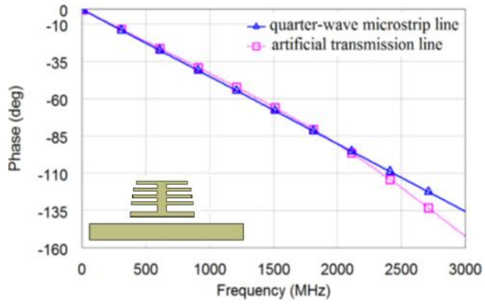

Figure 8. Electric lengths of conventional and artificial microstrip line segments.

For further analysis, it is necessary to verify the results of the numerical simulation with the measurement. For this purpose, using a method of etching printed circuit board we manufactured the 3-dB coupler prototype, shown in figure 9. After mounting the microwave connectors, we investigated this prototype by means of the vector network analyzer R&S ZVA24 operating in the frequency range from 10 MHz to 24 GHz. The measured S-parameters are shown in figure 10. The results of the numerical and experimental investigations are summarized in Table 1. It can be seen that the miniaturization efficiency (i.e. reduction in size while retaining the desired characteristics) obtained from experiments turned out to be worse than that obtained from numerical simulation. This is due to both manufacturing tolerances and possible differences in the substrate parameters.

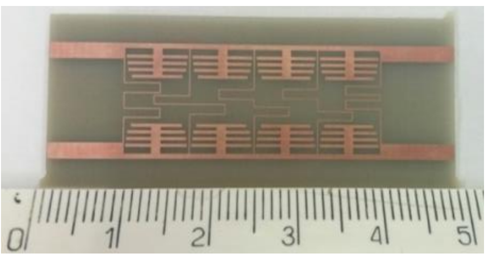

Figure 9. Manufactured prototype of the compact 3-dB coupler.

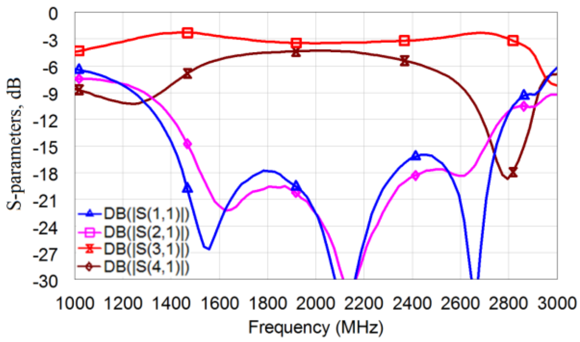

Figure 10. S-parameters of the manufactured compact 3-dB coupler.

Table 1. Designs comparison.

Parameters	*Standard*	*Compact (model)*	*Compact (layout)*
Bandwidth, MHz	1758	1375	1235
Relative bandwidth, %	87.9	68.75	61.75
Area, mm^2	2547	429.5	429.5
Relative area, %	100	16.85	16.85
Phase difference,°	90	89.3	88.5
Harmonic suppression	NO	YES	YES

3. Conclusion

In the present work we developed a miniaturized microstrip five-stub coupler tuned to the central operating frequency of 2000 MHz. The dimensions were reduced with the help of artificial transmission lines, whose lengths are smaller than the lengths of conventional quarter-wave segments. The placement of stubs in the free space inside the conventional layout made it possible to significantly reduce the area occupied by the coupler by 83.15%. At the same time, the operating frequency band was reduced by only 26.15%. Furthermore, a slight shift in the central operating frequency is observed with the designed coupler. This is probably due to the manufacturing tolerances or differences between the parameters of the substrates used for the simulation and the fabrication of the device. Further downsizing is possible by means of a more dense arrangement of the elements. However, this process leads to a further degradation in the frequency characteristics of the device.

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