A Design of Multi-Stage, Multi-Way Microstrip Power Dividers with Broadband Properties

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***Abstract* — We investigate a design method of multi-stage, multi-way microstrip power dividers to construct a compact low-loss power divider with numbers of outputs. First, we describe an integration design technique of multi-way power dividers founded on the planar circuit approach in combination with the segmentation method, and design broadband 3- and 4-way power dividers. Next, we successfully design a 9-way power divider consisting of 3-way dividers of two-stage structure using a similar technique. As a result, the fractional bandwidths of nearly 90%, 100%, and 85% are obtained, respectively. The validity of these design results is confirmed by HFSS and an experiment.**

***Index Terms* — Power dividers, microstrip components, multiport circuits, Chebyshev filters, design automation.**

I. INTRODUCTION

A power divider/combiner for RF power division and combination is one of the basic passive components and applied to many microwave and millimeter-wave systems and devices such as antenna feeders, power amplifiers, etc. Constituting principle of the divider/combiner is classified roughly into two groups; (1) a branch-line type divider which consists of two or more output lines branching in parallel from an input line [1],[2] and (2) a planar circuit type one which is designed by utilizing the two-dimensional current distribution (electromagnetic field) on a strip-conductor pattern [3],[4]. The former type requires matching networks such as quarter wavelength transformers, because the characteristic impedance of the input line usually differs from that of the parallel combination of the output lines. As the number of output lines increases, the characteristic impedance of the transformers is required to be a higher value, and the performance of the divider degrades due to the effect of parasitic reactance at the junction for branching. For the latter type, power dividers/combiners of circular and circular-sector shaped planar circuits are known. The operating principle of this type is based on the field distribution of resonant modes in the planar circuit, and therefore, narrow bandwidth is theoretically inevitable.

Generally, when we need so many power-splits that a single power divider does not answer the purpose, we may utilize a multi-stage structure such as tree-style 2^n-way power dividers consisting of n-stage, binary dividers. If an n-stage structure composed of N-way power dividers are employed, N^n-way power dividers can be realized, and thus more power-splits are achieved by less stages. Therefore, multi-way power dividers and multi-stage dividers utilizing them are useful for constructing low-loss compact power dividers with numerous output ports.

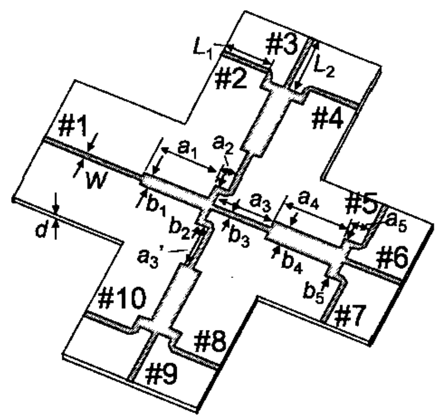

Fig. 1. Nine-way power divider consisting of 3-way dividers in 2-stage structure.

The present paper treats multi-stage, multi-way power dividers belonging to (1). In our case, the output lines branch from a low impedance line approximately equal to their combined impedance. Then the low impedance line is connected with an input line through a multi-section transformer to achieve broadband matching. First, we attempt an integration design of microstrip multi-way power dividers composed of multi-step, multi-furcation, and 90° and 45° mitered bends by the use of a CAD program based on the planar circuit approach along with the segmentation method. Though the structure is compact, some discontinuities are in close proximity to each other, and they often cause degradation of circuit characteristics. Therefore, the interaction among not only propagating modes but also non-propagating higher-order modes must be considered and its positive use is preferred. In addition, short computation time is requisite to determine the circuit configurations by using repetitious optimization algorithm.

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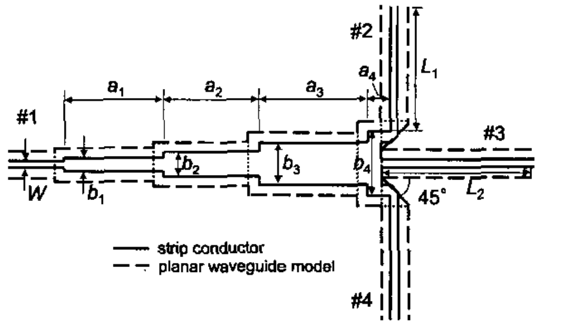

Fig. 2 Strip conductor pattern and planar circuit model of 3-way power divider.

Next, we design a double-stage 9-way power divider composed of 3-way dividers as shown in Fig. 1. In order to realize broadband characteristics, we use the three connecting lines of the first 3-way divider as two impedance steps combined in parallel for a three-step Chebyshev transformer.

As a result, broadband 3-, 4-, and 9-way power dividers with very flat equal-power-split property are obtained. Their fractional bandwidths are 90%, 100%, and 85% for the power-split imbalance less than 0.2dB and the return loss better than -20dB, respectively. The validity of the design results is confirmed by HFSS and an experiment.

II. Design Procedure

Figure 2 shows the circuit structure of a 3-way power divider integrated with 90° mitered bends connected at output ports. This circuit configuration can be synthesized from several rectangular and triangular shaped planar circuits. In this paper, we utilize the planar circuit approach (or two-dimensional circuit approach) and the segmentation/desegmentation method for designing and analyzing [5].

In Fig. 2, the solid lines indicate the actual strip conductor pattern. The broken lines represent the fictitious magnetic sidewalls derived from the planar waveguide model including fringing field effects at strip conductor edges. Namely, the widths of the conductors in the planar waveguide model are determined by considering the effective conductor width of the microstrip. We apply the planar circuit approach to the configuration surrounded by the broken lines. The actual circuit pattern can be obtained by subtracting the dimensions equivalent to fringing field effects from the planar waveguide model structure. The dotted lines in Fig.2 represent the dividing planes of the circuit necessary for the segmentation method and, in this case, the entire circuit is divided into 4 rectangular segments and 2 mitered bend segments. By deriving the Z-matrix of each segment on the basis of the planar circuit approach and connecting them under the continuity condition of the voltages and currents by the segmentation method [5], the entire Z-matrix of the 3-way power divider containing the effect of the higher order modes can be obtained, and hence we can compute the scattering matrix of the divider. The mitered bend segment is analyzed by removing a right-angled triangular segment from a rectangular segment, i.e. the desegmentation method is employed.

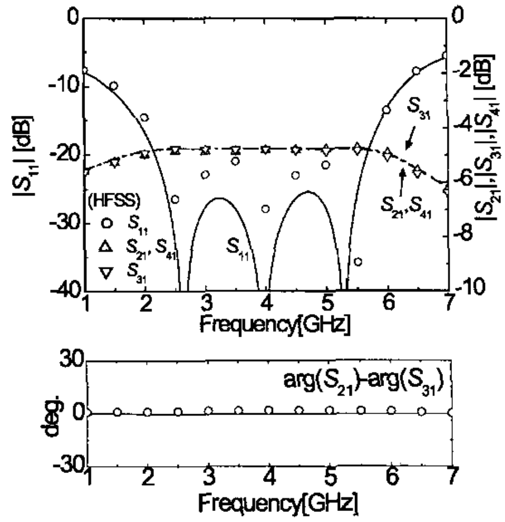

Fig. 3 Frequency characteristics of the S-parameters of the 3-way power divider corresponding to Fig. 2.

III. Design of Three- and Four-way Power Dividers

In this section, we design multi-way power dividers based on the above procedure. The relative permittivity and thickness of substrate are chosen as ε_r=10.3, d=0.64mm, respectively. The dimensions of the multi-stepped impedance transformer are chosen to be those of the Chebyshev transformer as initial value [6].

A. Three-way Power Divider with 90° Mitered Bends

Figure 3 shows the S-parameters and the dimensions of a 3-step, 3-way power divider with 90° mitered bends designed at a center frequency of 4GHz by employing the Powell's method [7] as a mathematical technique for optimization (a_i={7.10, 6.88, 7.80, 1.63}, b_i= {0.86, 1.73, 2.96, 4.60}, L_1=9.00, L_2=10.60, W=0.52 ; in mm). In optimization process, the dimensions of the circuit pattern are determined with consideration of the interaction between the transformer, 3-furcation and mitered bends. The equal power-split ratio ($|S_{21}|^2/|S_{31}|^2=|S_{41}|^2/|S_{31}|^2=1$) is realized by making the width b_4 of the junctions of the

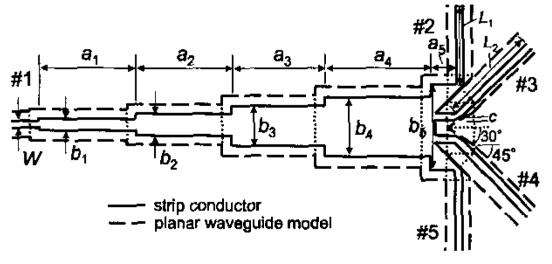

Fig. 4. Planar circuit model of a 4-way power divider.

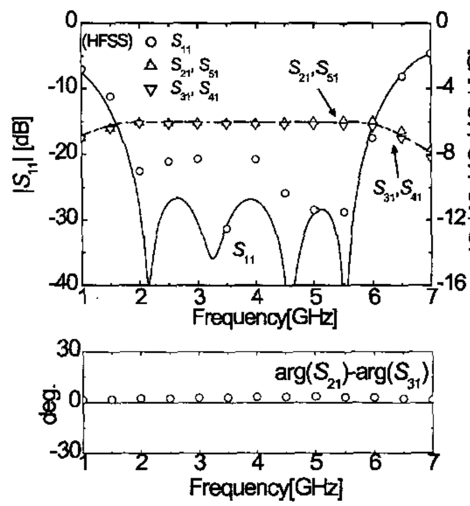

Fig. 5. Frequency characteristics of the S-parameters of the 4-step, 4-way power divider integrated with 90° and 45° mitered bends.

output ports 2 - 4 broader than the 50/3Ω microstrip width. The upper limit of operating frequency is determined from the width b_4 capable of suppressing higher order propagation modes. The center frequency is put at 4GHz from the consideration.

It is found that return loss smaller than -20dB and a flat 3-way equal power-split property are achieved over a considerable bandwidth. Its power-split imbalance is less than 0.1dB and the fractional bandwidth nearly 90%. Moreover, the phase difference between S_{21} and S_{31} becomes nearly 0 for an appropriate choice of the reference planes.

In addition, the design results are compared with the simulation results of the HFSS. Although S_{11} deteriorates slightly, both the results are in good agreement and the validity of this design technique is confirmed. We can guess that the differences of the return loss result from a slight disparity between the planar waveguide model and the actual fringing fields especially in the narrow spacing of strip conductors such as the 3-furcation and the notch of the bend. Also, because the reference planes of the planar waveguide model differ from the reference planes of the original microstrip pattern, they have to be shifted back adequately with consideration of the difference between the effective widths of the planar waveguide model and the actual widths of the microstrip lines.

B. Four-way Power Divider with 90° and 45° Mitered Bends

Secondly, an integration design of a 4-step, 4-way power divider with 90° and 45° mitered bends is performed in the same way as the 3-way power divider. The planar circuit model of the 4-way power divider is given in Fig.4. The 45° mitered bend is formed with a 30° slope because of limitations of available Green's functions. The 45° bend can be constructed from two rectangular circuits and three triangular circuits with skill. The details are omitted for the limited space.

Figure 5 shows the S-parameters of the 4-way divider obtained by optimizing the circuit dimensions a_i, b_i, c, and L_i (a_i={7.10, 7.01, 6.81, 7.78, 1.88}, b_i= {0.82, 1.56, 2.89, 4.37, 6.25}, c=0.33, L_1=9.58, L_2=10.00, W=0.52 ; in mm). It is found that good power-division properties of 6dB are realized. Its fractional bandwidth is 101%, amplitude difference less than 0.2dB, and the phase difference nearly 0. The configuration of the strip conductor for the 4-way branch lines is somewhat modified from the 3-way divider case. This structure plays an important role for realizing a very flat equal-power-division. In this case, a discrepancy between the waveguide model and the actual microstrip pattern is contained also. Slight separation of power split appearing around high frequency region may be caused by the influence of non-propagating higher order modes, since the frequency becomes close to the cut off value of the first higher order mode.

IV. Design of Nine-way Power Divider

Next, we attempt to design a 9-way power divider by uniting three 3-way dividers in two-stage structure as shown in the above-mentioned Fig. 1. Fig. 1 shows the structure of the 9-way power divider that contains 3-step Chebyshev transformer equivalently. An input 50-ohm line (width W) is connected with the first 3-way divider via an impedance step, and then three branch lines are connected with the second-stage 3-way dividers through the two impedance steps to be combined in parallel. All the characteristic impedance of nine output lines are chosen as 50 ohm (width W). Though the input line branches out into three lines on the way, this is basically a problem of matching a 50Ω line to a 50/9Ω line. The characteristic

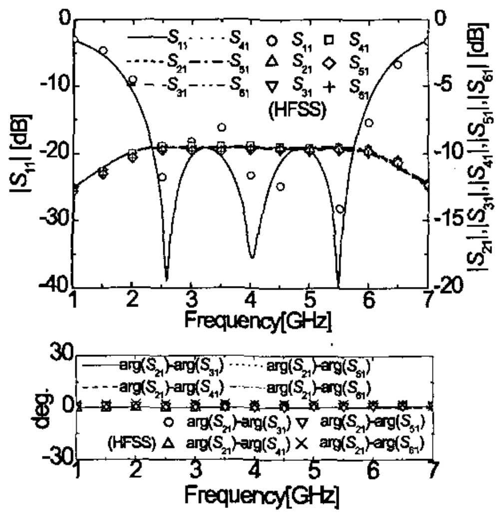

Fig. 6. Frequency characteristics of the S-parameters of the 2-stage, 9-way power divider optimized at 4GHz (corresponding to Fig. 1).

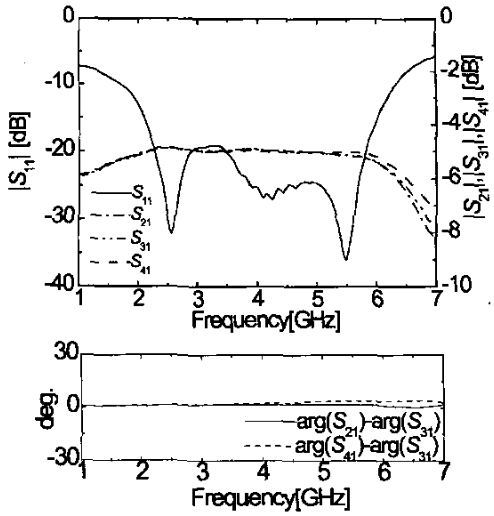

Fig. 7. Measured frequency characteristics of the S-parameters of the 3-step, 3-way power divider corresponding to that in Fig. 3.

impedances of the lines after branching can be estimated roughly from their combined impedances, which are equal to the original characteristic impedances of the Chebyshev transformer. The dimensions of the 3-furcation, 90° mitered bends, and 3 output lines must be determined by considering their mutual effects so as to work as the second section of the Chebyshev transformer.

Figure 6 shows the S-parameters of the 9-way power divider obtained by optimization (a_i={6.46, 1.35, 3.76, 6.66, 1.67}, b_i= {1.29, 4.45, 0.55, 2.08, 4.33}, a_3'=5.90, L_1=4.74, L_2=5.74, W=0.52 ; in mm). It is found that good 9-way power division properties are realized. Its fractional bandwidth is 85%, amplitude difference less than 0.2dB, and the phase difference between outputs nearly 0. The results agree well with the results simulated by the HFSS.

V. EXPERIMENT

The 3-way power divider corresponding to that in Fig. 3 was fabricated as a trial and the frequency characteristics of the S-parameters were measured. The results are shown in Fig. 7. It is found that good results are obtained, and hence the validity of the design technique is confirmed.

VI. CONCLUSION

We designed the broadband multi-way power dividers with compact structure on the basis of the planar circuit approach and the segmentation and/or desegmentation method. The dividers possess very wide bandwidth, i.e., the fractional bandwidth of nearly 90% for the 3-way divider, 100% for the 4-way divider, and 85% for the 9-way divider. The validity of the design technique was confirmed by comparing the design results with the simulation results of HFSS and an experiment.

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