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BROADBAND ASYMMETRICAL MULTI-SECTION COUPLED LINE WILKINSON POWER DIVIDER WITH UNEQUAL POWER DIVIDING RATIO

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Abstract—The uniform asymmetrical microstrip parallel coupled line is used to design the multi-section unequal Wilkinson power divider with high dividing ratio. The main objective of the paper is to increase the trace widths in order to facilitate the construction of the power divider with the conventional photolithography method. The separated microstrip lines in the conventional Wilkinson power divider are replaced with the uniform asymmetrical parallel coupled lines. An even-odd mode analysis is used to calculate characteristic impedances and then the per-unit-length capacitance and inductance parameter matrix are used to calculate the physical dimension of the power divider. To clarify the advantages of this method, two three-section Wilkinson power divider with an unequal power-division ratio of $1:2.5$ are designed and fabricated and measured, one in the proposed configuration and the other in the conventional configuration. The simulation and the measurement results show that not only the specified design goals are achieved, but also all the microstrip traces can be easily implemented in the proposed power divider.

1. INTRODUCTION

The Wilkinson power divider is widely used as a feed structure for planar antennas and microwave circuits because of its well-described design method, simple of construction [1–4]. It can provide almost flat power division appropriate ports matching over its bandwidth and effective isolation between the output ports. Some applications need broadband multi-section microstrip Wilkinson power divider with

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unequal power division ratio. However, for this kind of power divider the characteristic impedance of some of the microstrip lines becomes high which finally leads to the narrow strip width [5]. The narrow strip width is not desirable because of the extra insertion loss, power handling reduction and difficulty of manufacturing.

Several methods have been proposed in the literatures to overcome the narrow strip width in single section Wilkinson power divider with high dividing ratio [6–18]. They can be divided into three categories. In the first category, defected ground structure (DGS) has been used in order to achieve the required high characteristic impedance and avoiding narrow strip width [6–8]. This method is straightforward for designing but the ground plane should be kept far from the other ground planes.

The second category has tried to replace the conventional microstrip lines of the conventional microstrip Wilkinson power divider with another transmission lines such as double-sided parallel strip-lines (DSPSL), dual transmission lines or even grooved substrate microstrip line [9–11]. This methods lead to achieve very high characteristic impedance which is needed for implementation of the Wilkinson power divider with very high dividing ration.

In the third category, the proposed methods try to add some extra microstrip lines to the middle or at the output nodes of the conventional microstrip Wilkinson power divider [12–15]. These approaches are very easy to implement but in some cased the bandwidth is reduced a bit.

The application of the asymmetrical coupled lines for designing Wilkinson power divider was first introduced in [16]. The design method starts by decomposing the three port network into two networks and the even- and odd-mode analysis is applied to one network. The parameters of the other network are related to the first network from the impedance scaling factor. The equivalent even-mode network is used to derive the even-mode characteristic impedance of each section of the power divider in order to obtain the desired power division ratio and input voltage standing wave ratio (VSWR) in all ports. The odd-mode network including the coupling scheme is used to derive the isolation resistor of each section.

In [17] the asymmetrical microstrip coupled-line has been mainly proposed for circuit size reduction. The design procedure has been proposed based on the even- and odd-mode analysis which leads to unequal power division between arbitrary terminated output ports.

The application of asymmetrical uniform microstrip coupled lines has been proposed to overcome the shortcoming of the narrow strip width of the single section Wilkinson power divider with high dividing ratio [18]. The application of asymmetrical uniform microstrip coupled lines is mainly proposed for avoiding the narrow strip width in wideband multi-secsion microtstrip Wilkinson power divider. The proposed method overcomes this problem by replacing the separated microstrip branches with uniform asymmetrical microstrip coupled lines. It is shown that for 1 : 2.5 power division ratio, the strip width of the designed Wilkinson power divider is significantly greater than the strip width of the conventional Wilkinson power divider with the same power division.

2. DESIGN PROCEDURE

Figure 1 shows the layout of the multi-section Wilkinson power divider implemented by using the asymmetrical uniform microstrip parallel coupled lines including its various parameters. The Wilkinson power divider is similar to the conventional multi-section Wilkinson power divider except that the isolated microstrip transmission lines in the conventional Wilkinson power divider are replaced by asymmetrical uniform parallel coupled lines.

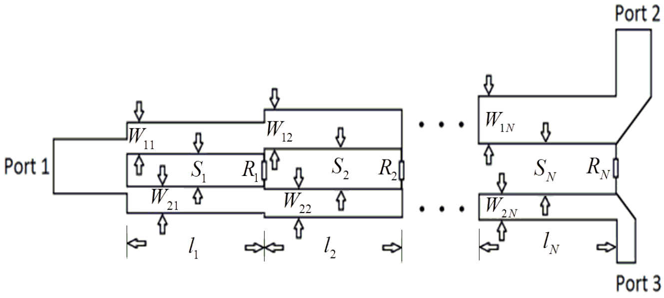

Figure 1. Layout of the multi-section Wilkinson power divider including its various parameters.

The power divider consists of N sections. The trace width of upper and lower lines and the isolation resistor of the nth section are denoted by W_{1n}, W_{2n} and R_n, respectively. The gap spacing and the length of section N are also denoted by S_n and l_n, respectively. The design goal is to determine the parameters of each section (W_{1n}, W_{2n}, S_n, l_n and R_n) of the power divider such that in addition to the desired isolation and power division between the output ports acceptable reflections at all ports are also achieved.

Approximately similar design procedure introduced in [16] is followed for designing the Wilkinson power dividers. For achieving this goal, first the three port network is decomposed into two groups of networks for even- and odd-mode with appropriate parameter definitions. Then, each even- and odd-mode network consists of a terminated four-port which half of it is identical to the other by impedance scaling factor. The impedance scaling factor is equal to the power division ratio between the output ports. The terminated impedance at port 1 is equal to Z_0. The even-mode networks are similar to the multi-section quarter wave transformers. So, the characteristic impedances of the even mode are easily derived. For the odd mode the characteristic impedances of each section is derived according to the coupling coefficient and even mode characteristic impedance for that section. The coupling coefficients are not unique but too strong coupling should be avoided because it leads to negative odd-mode characteristic impedances. Finally a simple program has been written in MATLAB for calculating the resistor values. The resistor values are calculated such that the reflection coefficients of the even- and odd-mode have the same zeros.

For calculating the physical dimensions of the designed Wilkinson power divider, the capacitance matrixes of an asymmetrical uniform microstrip coupled lines for various strip widths and gap spacing over air and dielectric substrates are obtained and then tabulated [19]. It is supposed that substrate is FR4 with a thickness of 1.57 mm with approximate dielectric constant equal to 4.4.

Figures 2(a) and 2(b) show the cross section of the microstrip asymmetrical coupled lines over a dielectric and air substrates, respectively. The equivalent capacitance networks are also shown for dielectric and air substrates in Fig. 2(a) and Fig. 2(b), respectively. C_{11} and C_{22} are defined as equivalent self-capacitances for microstrip asymmetrical coupled lines over dielectric substrate while C_{11}^0 and C_{22}^0 are defined as equivalent self-capacitances for microstrip asymmetrical coupled lines over air substrate. The mutual capacitances for microstrip asymmetrical coupled lines over dielectric and vacuum substrates are also defined as C_{12} and C_{12}^0, respectively.

The equivalent capacitance networks can also be decomposed into two parts for the even- and odd-mode as shown in Fig. 2(a) and Fig. 2(b). For the even mode, a magnetic wall can be defined between two lines. So the effective capacitances between strip conductors and ground are

$$C_{1e} = C_{11} \tag{1}$$

$$C_{2e} = C_{22} \tag{2}$$

$$C_{1e}^0 = C_{11}^0 \tag{3}$$

$$C_{2e}^0 = C_{22}^0 \tag{4}$$

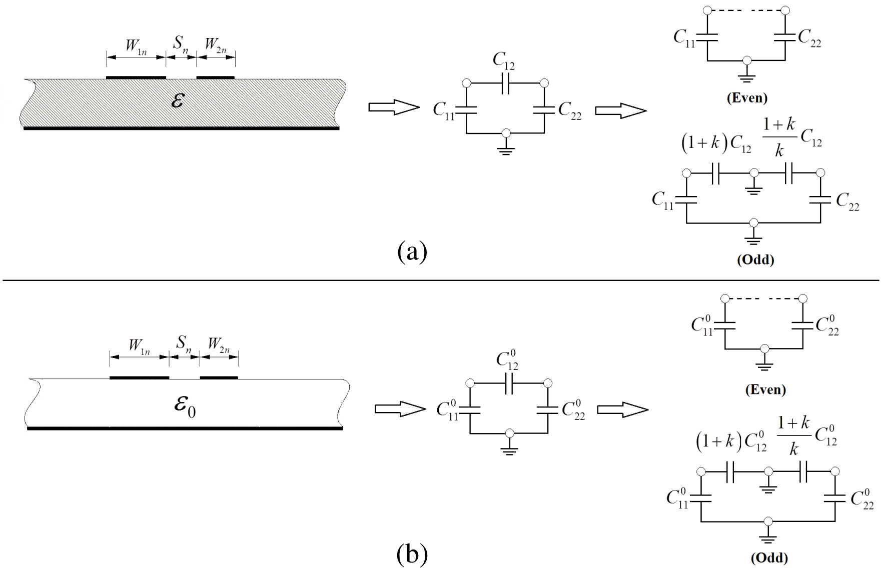

Figure 2. The cross section of uniform asymmetrical coupled lines over dielectric and vacuum substrates including equivalent capacitance networks.

where C_{1e} and C_{2e} are the even mode effective capacitances of the microstrip asymmetrical coupled lines over dielectric substrate for the first and second strips, respectively. C_{1e}^0 and C_{2e}^0 are also the even mode effective capacitances of the microstrip asymmetrical coupled lines over air substrate for the first and second strips, respectively. For the odd mode, an electric wall can be defined between lines in appropriate position. This leads to effective capacitances between strip conductors and ground as

$$C_{1o} = C_{11} + (1+k)\,C_{12} \tag{5}$$

$$C_{2o} = C_{22} + \left(\frac{1+k}{k}\right)C_{12} \tag{6}$$

$$C_{1o}^0 = C_{11}^0 + (1+k)\,C_{12}^0 \tag{7}$$

$$C_{2o}^0 = C_{22}^0 + \left(\frac{1+k}{k}\right)C_{12}^0 \tag{8}$$

where C_{1o} and C_{2o} are the odd mode effective capacitances of the microstrip asymmetrical coupled lines over dielectric substrate for the first and second strips, respectively. C_{1o}^0 and C_{2o}^0 are also the odd mode effective capacitances of the microstrip asymmetrical coupled lines over vacuum substrate for the first and second strips, respectively. k is also the power division ratio. The characteristic impedances for even- and odd-mode are then easily calculated from the effective capacitances by [20]

$$Z_{0e}^{1} = \frac{1}{c\sqrt{C_{1e}C_{1e}^{0}}} \tag{9}$$

$$Z_{0e}^{2} = \frac{1}{c\sqrt{C_{2e}C_{2e}^{0}}} \tag{10}$$

$$Z_{0o}^{1} = \frac{1}{c\sqrt{C_{1o}C_{1o}^{0}}} \tag{11}$$

$$Z_{0o}^{2} = \frac{1}{c\sqrt{C_{2o}C_{2o}^{0}}} \tag{12}$$

where c is the light speed in vacuum. In the next step, another simple program has been written in MATLAB. The program calculate the even- and odd-mode characteristic impedances for the uniform microstrip asymmetrical coupled lines based on the aforementioned discussion and by using the tabulated capacitance matrixes. Then, according to the calculated even- and odd-mode characteristic impedances and the characteristic impedances of the designed power divider, the program looks for the corresponding physical dimensions.

3. DESIGNING OF THE POWER DIVIDER AND RESULTS

In order to demonstrate the effectiveness of applying uniform microstrip asymmetrical coupled lines instead of isolated coupled lines in multi-section Wilkinson power divider for elimination the narrow strip widths, a sample of the power divider with 1 : 2.5 power division and bandwidth of 96% is designed with the FR4 substrate with a thickness of 1.57 mm and approximate dielectric constant equal to 4.47 Furthermore, the designed power divider has three sections and the coupling coefficients are $c_1 = 0.377$, $c_2 = 0.268$ and $c_3 = 0.165$. The strongest coupling is for the first section while the weakest coupling is for the last section and they are experimentally chosen so that the width of the lines would be wide enough that can be fabricate easily.

The dimensions of the designed Wilkinson power divider are shown in Table 1. The terminated resistor values are selected according to the standard resistor values. The final values of the terminated resistors are also included to the Table 1.

For comparative reason, another multi-section Wilkinson power divider consists of isolated microstrip lines with the same specifications

Table 1. The dimensions of the designed multi-section Wilkinson power divider.

$\varepsilon_r = 4.47$ $h = 1.6\,\text{mm}$ $\Gamma_m = 0.05$ $f_0 = 1.5\,\text{GHz}$ coupled factors = {0.165 0.268 0.377}										
n	k	S_1	S_2	S_2	W_{11}	W_{12}	W_{13}	W_{21}	W_{22}	W_{23}
3	2.5	0.601	1.16	1.71	3.5	4.62	5.9	0.381	0.679	1.167
length of lines					29.2	28.8	28.4	29.2	28.8	28.4
Initial resistor values		$R_1 = 73.68$			$R_2 = 193.42$			$R_3 = 1361.25$		
Selected resistor values		$R_1 = 75$			$R_2 = 180$			$R_3 = 1300$		

Table 2. The dimensions of the conventional multi-section Wilkinson power divider.

$\varepsilon_r = 4.47$ $h = 1.6\,\text{mm}$ $\Gamma_m = 0.05$ $f_0 = 1.5\,\text{GHz}$ coupled factors = {0 0 0}										
n	k	S_1	S_2	S_2	W_{11}	W_{12}	W_{13}	W_{21}	W_{22}	W_{23}
3	2.5	30	30	30	2.15	3.3	5	0.137	0.348	0.819
length of lines					27.5	27	26.6	29.7	29	28.54
Calculated resistors in MATLAB		$R_3 = 97$			$R_2 = 228$			$R_3 = 673$		

is designed. The same procedure is followed for designing the new power divider. In this regard, the coupling confections are considered to be equal to zero. The various dimensions of the new power divider are shown in Table 2.

It is indicated by comparing the various dimensions of the power dividers that the widths of all traces of the Wilkinson power divider consist of the uniform asymmetrical coupled lines are larger than the conventional multi-section Wilkinson power divider. All the trace widths of the multi-section Wilkinson power divider consist of the uniform asymmetrical coupled lines are appropriated for construction while in the conventional multi-section Wilkinson power divider the narrowest strip width of the first section is equal to 0.137 mm that is difficult to construct with conventional photolithography.

Both of the designed Wilkinson power dividers have been fabricated over the FR4 board.

Figures 3 and 4 show the fabricated circuits. The scattering parameters of the designed power dividers have been measured. Fig. 5 to Fig. 10 show the measured scattering parameters of the fabricated power dividers. Fig. 5 shows the magnitude of the reflection coefficient at port 1. As the figure shows, the magnitude of the reflection coefficient for both cases is below −15 dB in entire bandwidth.

Figures 6 and 7 show the power division between the output ports.

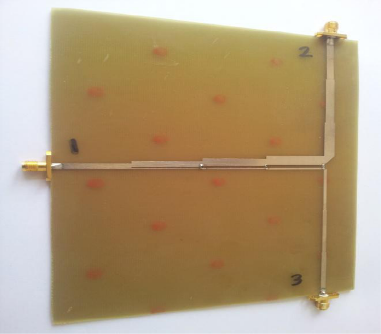

Figure 3. Photograph of the constructed power divider consists of the microstrip asymmetrical coupled lines.

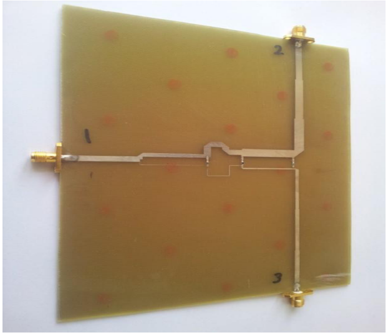

Figure 4. Photograph of the constructed power divider consists of isolated microstrip lines.

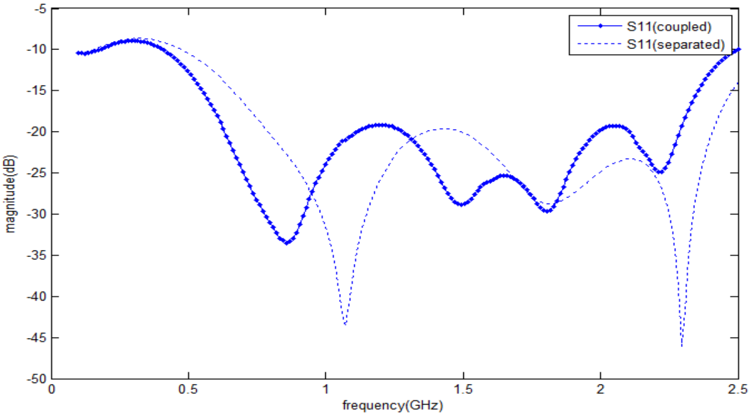

Figure 5. Reflection coefficient versus frequency at port 1.

The level of the power division at midband at port 2 of the power divider consists of the microstrip asymmetrical coupled lines and the power divider consists of the isolated microstrip lines are 2 dB and 2.3 dB, respectively. The level of the power division at midband at port 3 of the power divider consists of the microstrip asymmetrical coupled lines and the power divider consists of the isolated microstrip lines are 7.2 dB and 6.4 dB, respectively. According to design specifications, the desired power division at port 2 and port 3 are approximately equal 1.5 dB and 5.5 dB, respectively. Comparison between the achieved power divisions and the power division goal shows extra insertion

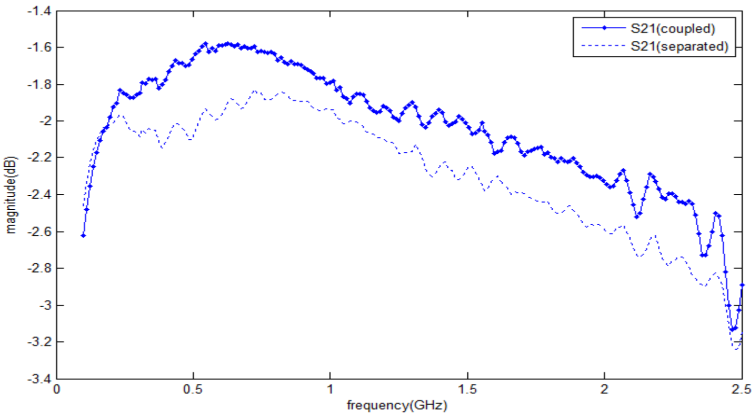

Figure 6. Measured power division versus frequency at port 2.

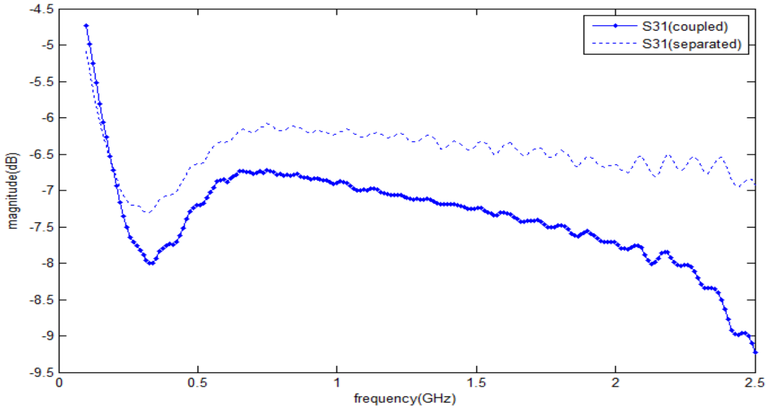

Figure 7. Measured power divisions versus frequency at port 3.

losses. The extra insertion losses are somewhat due to the construction errors and somewhat due to the high level of FR4 loss tangent.

Figure 8 shows the isolation between the output ports of the designed power dividers. The figure shows that the isolation between output ports for both cases is below −25 dB in entire bandwidth. Fig. 9 and Fig. 10 show the reflection coefficients at port 2 and port 3, respectively. According to these figures, the reflection coefficients at output ports for the designed power dividers are below −15 dB in entire bandwidth. Except for the extra losses, the measured parameters of the power divider are in accordance with the design specifications.

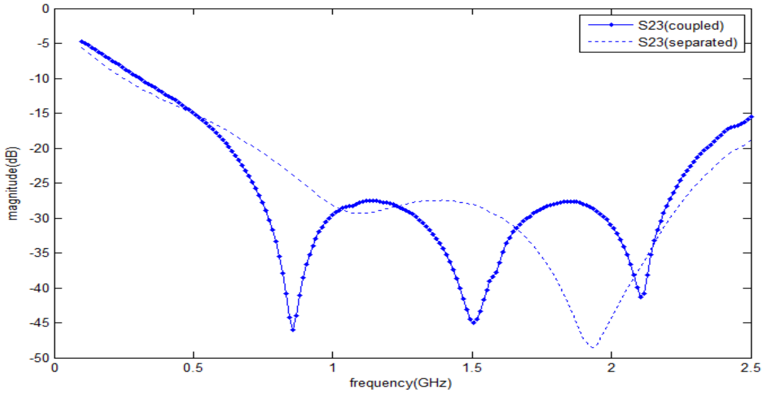

Figure 8. Measured isolation versus frequency between the output ports.

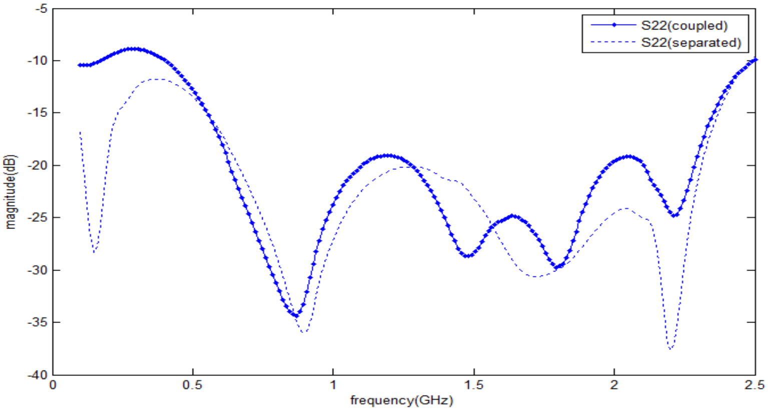

Figure 9. Reflection coefficient versus frequency at port 2.

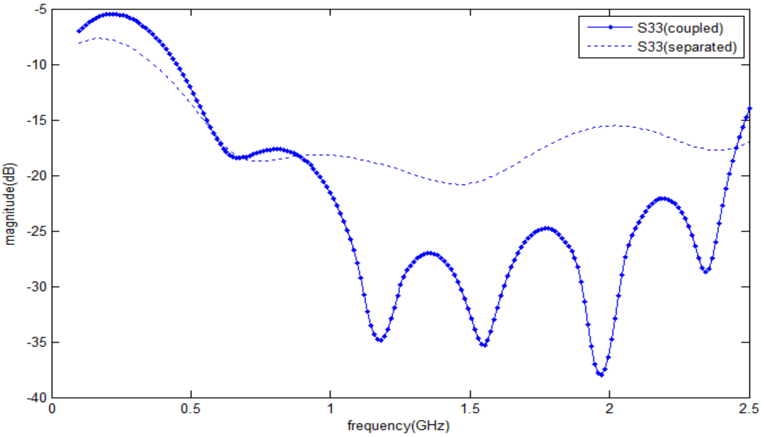

Figure 10. Reflection coefficient versus frequency at port 3.

4. CONCLUSION

Broadband multi-section Wilkinson power dividers were designed and tested. One of the designed power divider has conventional topology while in the other one the isolated microstrip transmission lines were replaced with the microstrip uniform asymmetrical coupled lines. A suitable design procedure was followed which lead to designing of the power dividers. Comparing the various dimensions of the Wilkinson power divider showed that all traces of the power divider consists of the microstrip uniform asymmetrical coupled lines were wider than the Wilkinson power divider consists of the isolated microstrip lines. The designed power dividers were constructed on FR4 substrate and their scattering parameters were measured. The measurement results showed a good agreement between the power divider specifications and specified design goals.

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