Progress In Electromagnetics Research, PIER 76, 243–252, 2007

A NOVEL COMPACT PLANAR SIX-WAY POWER DIVIDER USING FOLDED AND HYBRID-EXPANDED COUPLED LINES

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Abstract—A novel planar six-way power divider is proposed. Based on the conventional planar microstrip coupled line technology, the proposed compact six-way power divider is comprised of two stages coupled transmission lines, which is different to the conventional multi-stage power divider using the same expanded structure, one stage folded two-coupled line, and the other hybrid-expanded symmetrical three-coupled line. Therefore, the proposed power divider is size reduction, and has a broad-band property, which is better than 40% of fractional bandwidth. Furthermore, compared to a traditional six-way power divider, it is designed and fabricated easily. From the simulated and measured results, the six-way planar power divider shows a good specifications, which are insert loss 8.1±0.2 dB from 2 GHz to 3 GHz, and return loss less than −18 dB, isolation less than −19.5 dB at 2.5 GHz, respectively.

1. INTRODUCTION

Power dividers are widely used in radar, communication and high frequency applications. In the conventional circuit design, the circuits for an even number of two or more output signals have been proposed [1–5], which are good for an even number of output ports, but it is still difficult to design power dividers with an odd number of output ports. A new three-way power divider was proposed [6], which can modify a three-way Wilkinson power divider from a three-dimensional configuration into a two-dimensional one, and reduce the circuit dimension down to $\lambda/4$ with only two isolation resistors and is most suitable to be implemented in a planar form. However, if the number of output ports is more than three, the practical planar circuit PCB layout and fabrication will become difficult, and the bit error rate of signal transmission within couple lines becoming increased. A miniaturized low-loss Wilkinson power divider for RF front-end applications was proposed [7], whose reduction of size was implemented by folding the quarter-wave transmission lines into tightly coupled meander lines. A planar low-loss electrically symmetric eight-way hybrids that resemble the Wilkinson hybrid were introduced-the "radial" hybrid [8–10]. In essence, however, the combined amplifier using two such hybrids would be non-planar for the input/output port using the coaxial line to transmit signal. Moreover, unlike the Wilkinson hybrid, the match and isolation of the radial and the fork hybrids are not perfect even at the center frequency.

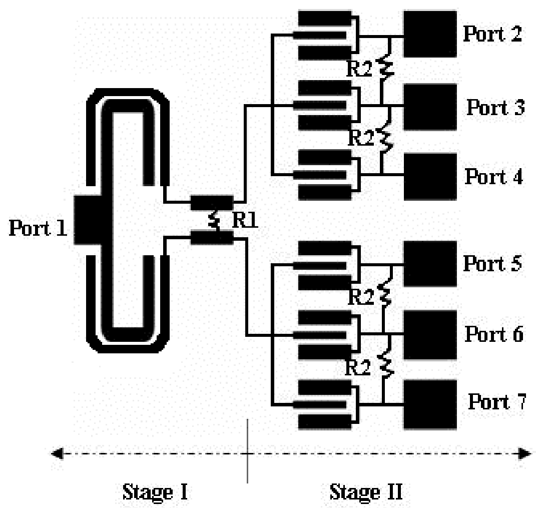


Figure 1. The circuit topology of the proposed six-way power divider.

In this paper, a new fully planar six-way power divider is proposed which can reduce the circuit structure to 2-dimension and fabricate physical size with only five isolation resistors. The proposed compact six-way power divider is comprised of two stages coupled line, which is different to the conventional multi-stage power divider using the same expanded structure, one stage folded two-coupled line, and the other one hybrid-expanded symmetrical three-coupled line. On one hand, circuit size reduction can be implemented by the folding the quarter-wave coupled transmission lines into tightly coupled meander lines. Therefore, to some extent, the folding technology can overcome the limit of the physical size for the structure with $\lambda/4$, especially below the X-band or if low-permittivity substrate materials are employed.

On the other hand, with the hybrid-expanded technology, it is not only possible to increase the flexibility of design and manufacture easily the circuit on the PCB, but expand greatly the operating bandwidth of the power divider. Furthermore, implementation of the coupled line technique can provide the dc block function as well, which can further reduce the parasitic effects from the use of extra blocking capacitors.

2. ANALYSIS AND DESIGN OF THE SIX-WAY POWER DIVIDER

2.1. Analysis of the Power Divider

The configuration of the proposed six-way power divider is shown in Fig. 1, which consists of two $\lambda/4$ folded two-coupled transmission lines and six $\lambda/4$ symmetrical three-coupled lines, with five additional isolation resistors. Therefore, the analytic method of the proposed power divider with coupled lines is divided into two parts, i.e., one is to analyze two-way folded structure of coupled line, which is analyzed easily with the even- and odd-mode technique since the condition of equal amplitude and in-phase excitation is easily achieved [11–16]. The other is to focus on the impedance matching of different microstrip line interfaces to successfully transform an incoming signal into six parts.

In Stage I, an incoming signal is separated into two parts with equivalent amplitudes and with good impedance matching. Therefore, the input port impedance, $Z_{in} = 50\,\Omega$, is matched to the two equivalent microstrip lines with load terminated impedance Z_L, which is the input impedance of the next stage. The operational principle of two-coupled line behaviors is shown as Figure 2.

In the Figures 2(a) and 2(b), we can define an even mode voltage V_e and current I_e and an odd mode voltage V_{od} and current I_{od} in terms of the total voltages and currents at the ports 1 and 2 such that:

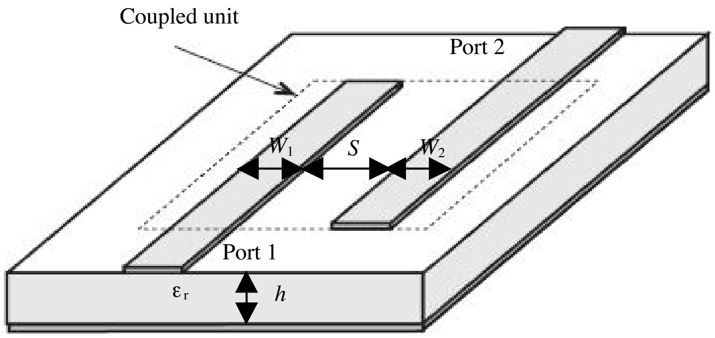
$$V_e = \frac{1}{2}(V_1 + V_2), \qquad I_e = \frac{1}{2}(I_1 + I_2) \tag{1a}$$

and

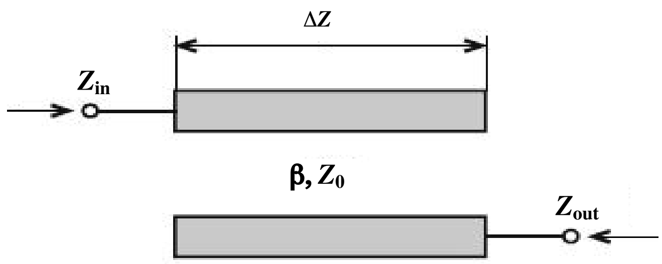
$$V_{od} = \frac{1}{2}(V_1 - V_2), \qquad I_{od} = \frac{1}{2}(I_1 - I_2) \tag{1b}$$

According to the above odd-mode and even-mode definition and the equivalent circuit topology in the Figure 2(c), we can obtain a set of first-order, coupled ordinary differential equations:

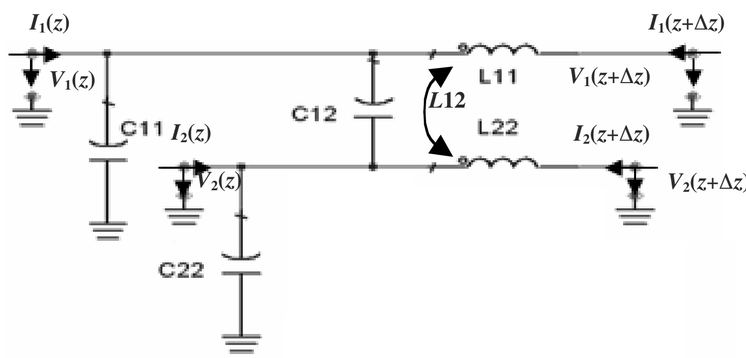
$$\begin{cases} -\dfrac{dV_e}{dz} = j\omega(L_{11} + L_{12})I_e & \text{(2a)} \\ -\dfrac{dI_e}{dz} = j\omega(C_{11} + C_{12})V_e & \text{(2b)} \end{cases}$$



(a) coupled unit of parameters representation in the stage I



(b) transmission line representation of the coupled unit



(c) Equivalent circuit topology of the two lossless coupled unit

Figure 2. Analysis of two-coupled transmission line unit behavior.

and

$$\begin{cases} -\dfrac{dV_{od}}{dz} = j\omega(L_{11} - L_{12})I_{od} & \text{(2c)} \\ -\dfrac{dI_{od}}{dz} = j\omega(C_{11} - C_{12})V_{od} & \text{(2d)} \end{cases}$$

Then, we decouple the governing equations, and get the characteristic impedances Z_{0e} and Z_{0od} for the even and odd modes:

$$Z_{0e} = \frac{1}{\upsilon_{pe} C_e}, \qquad Z_{0od} = \frac{1}{\upsilon_{pod} C_{od}} \tag{3}$$

Where,

C_e, C_{od}-even and odd mode capacitances, respectively;

$\upsilon_{pe}, \upsilon_{pod}$-even and odd mode phase velocities, respectively.

For these capacitances are very complex, we have to resort to a numerically computed impedance grid or computer simulation.

According to Gupta [12], this configuration has the impedance matrix coefficients for open transmission line segments in the following form:

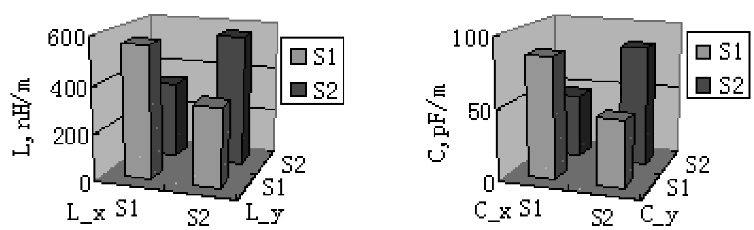
$$Z_{11} = -j\frac{1}{2}(Z_{0e} + Z_{0od})\cot(\beta l) = Z_{22} \tag{4a}$$

$$Z_{12} = -j\frac{1}{2}(Z_{0e} - Z_{0od})\frac{1}{\sin(\beta l)} = Z_{21} \tag{4b}$$

When cascading the coupled unit into the power divider configurations, we can find the image impedances above equations. Finally, according to the definition of ABCD chain matrix, we can obtain the following input impedance formula:

$$Z_{in} = \frac{1}{2\sin(\beta l)}\sqrt{(Z_{0e} - Z_{0o})^2 - (Z_{0e} + Z_{0o})^2 \cos^2(\beta l)} \tag{5}$$

From above equations, we can design the stage I circuit of power divider if the even- and odd- mode parameters of matrix [$\boldsymbol{L}$] and [$\boldsymbol{C}$] are obtained for the two-coupled line [17–19]. In this paper, we find the mode parameters of two-coupled line with the CAD tools and plot the data with 3-dimension form, as following Figure 3. From



(a) 3-dimension inductance matrix (b) 3-dimension capacitance matrix

Figure 3. Calculated characteristic parameters of two-coupled transmission line.

the 3-D curves, we can find that the coupled capacitances and cross-coupled inductances are enough to couple the energy from input to output. The conclusion is drawn by the S-parameters simulation, as shown following Figure 4. Obviously, the two-coupled line consisting of stage I circuit has shown an excellent transmission performance and appropriate terminated matching.

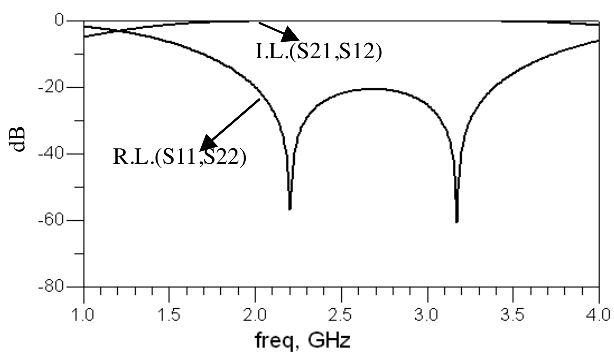


Figure 4. Simulated results of two-coupled transmission line behavior.

In stage II, with the help of reference paper [6], we can analysis and design the symmetrical three-coupled lines. Therefore, there is no more about the description of the analysis.

2.2. Synthetic Design of the Power Divider

According to analyze above Section 2.1, we can divide the topology of circuit into two parts during the design process of power divider, as discussed in the previous analysis. With the simulation tool, we can optimize the power divider, and finally, obtain the requirement results. The planar six-way power divider is designed as shown in Figure 5. A low-cost FR4 PCB with the dielectric constant of 4.7 and 2.0-mm-thick is used. The overall dimension of the circuit is about 4.8 cm×3.0 cm.

3. RESULTS AND DISCUSSION

According to the above analysis and design process, we simulate and optimum the six-way planar power divider with RF/Microwave circuit simulator. From the simulated results, as shown in Fig. 6, the insertion loss of the six output-ports is about 8.1±0.2 dB, which are very good agreements with theoretical analysis. According to reference [6], the two three-coupled transmission line units corresponding respectively to port 3 and 6 are different slightly to the other coupled line

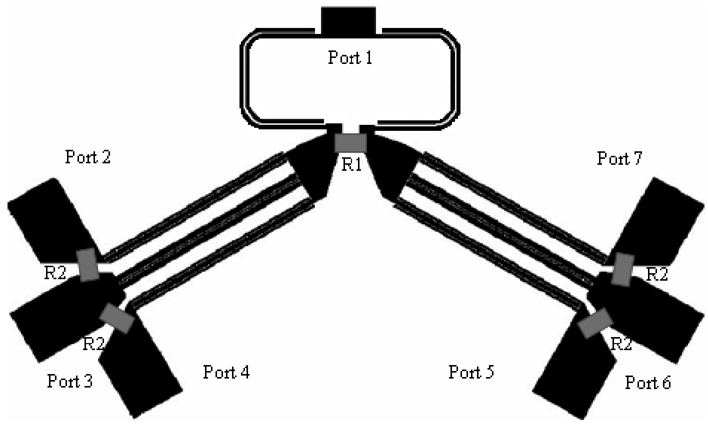


Figure 5. The six-way power divider PCB layout.

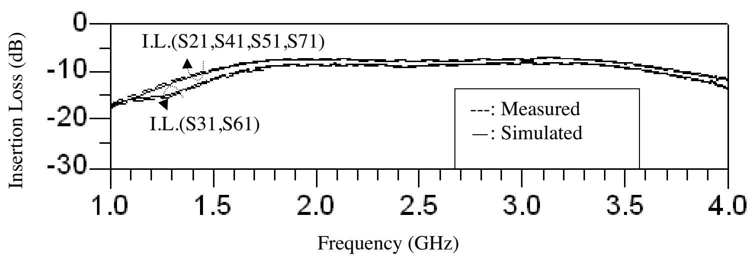


Figure 6. Simulated and the measured insertion loss of the power divider.

units for the sizes of structure . Meanwhile, due to the error of calculation in the design, S31 and S61 are different slightly to the other transmission parameters S21, S41, S51, and S71 at the range of operational frequency. Additionally, as shown in Fig. 6, the bandwidth of the power divider is from 2 GHz to 3 GHz with very good agreements. The band-width of the circuit can be controlled and adjusted by the spacing between the coupled lines. To increase the bandwidth, thin film process can be used to obtain the smaller spacing less than 0.1 mm. The smaller the spacing, the wider the bandwidth [6].

The return loss of the six outputs is shown in Fig. 7. From the simulated results, the circuit provides acceptable return losses in the output ports which are better than 18 dB at 2.5 GHz. Therefore, the designed circuit can match to the each port of the power divider.

The simulated isolation of the each port are shown in Fig. 8.

From the simulated curves, pretty good results can be achieved which isolations between each port are better than 19.5 dB at 2.5 GHz. It shows that the six output ports have good isolation among each other. Similar concepts can also be implemented in power combiners.

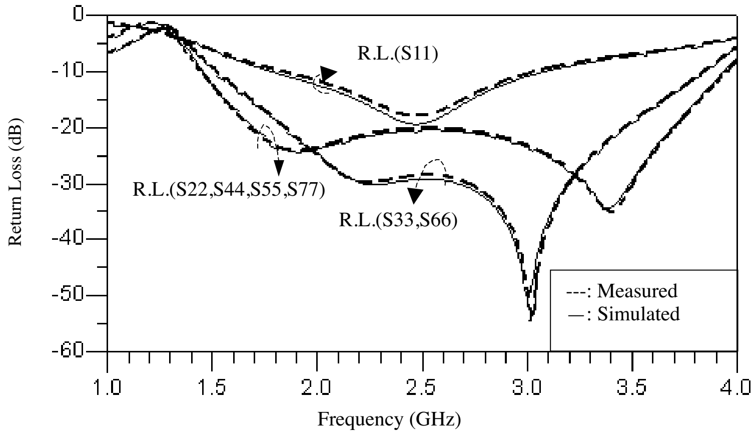


Figure 7. Simulated and the measured return loss of the power divider.

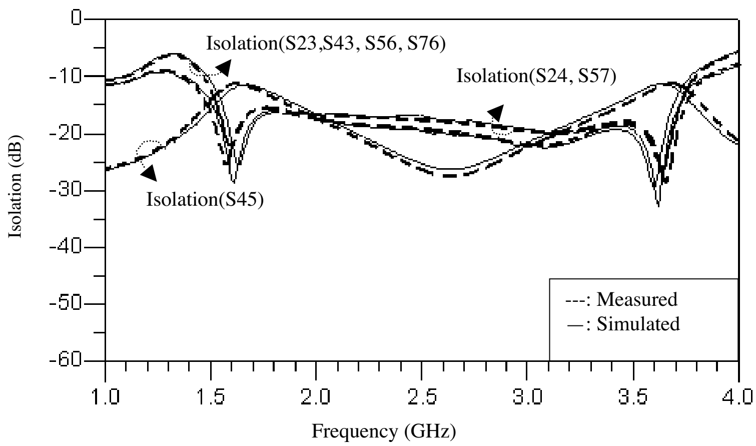


Figure 8. Simulated and the measured isolation of the power divider.

4. CONCLUSION

In this paper, we analysis and design the planar six-way power. With the folded microstrip coupled transmission line and hybrid-expanded symmetric coupled line which can provide the dc block function, which further reduce the parasitic effects from the use of extra blocking capacitors. In addition, only five isolation resistors, the power divider implements two stages transform, therefore, reducing the parasitic effects of the resistors. The performance of this compact circuit is improved greatly. The results of simulation are insert loss 8.1 ± 0.2 dB from 2 GHz to 3 GHz, return loss less than -18 dB, isolation less than -19.5 dB at 2.5 GHz, respectively. The overall design results can achieve completely the engineering requirements.

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