ULTRA WIDEBAND POWER DIVIDER USING TAPERED LINE

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Abstract—A power divider with ultra-wideband (UWB) performance has been designed. The quarter-wave transformer in the conventional Wilkinson power divider is replaced by an exponentially tapered microstrip line. Since the tapered line provides a consistent impedance transformation across all frequencies, very low amplitude ripple of 0.2 dB peak-to-peak in the transmission coefficient and superior input return loss better than 15 dB are achieved over an ultra-wide bandwidth. Two additional resistors are added along the tapered line to improve the output return loss and isolation. Simulation performed using CST Microwave Studio and measured results confirm the good performance of the proposed circuit. The return loss and the isolation between the output ports are better than 15 dB across the band 2–10.2 GHz. Standard off-the-shelf resistance values can be selected by optimizing the physical locations to mount the resistors. Better performance can be achieved with more isolation resistors added. Hence, the number of isolation resistors to be used may be selected based on the desired bandwidth and level of isolation and return loss specifications.

1. INTRODUCTION

Power dividers are passive devices which are widely used in microwave systems. It is used to distribute input signal power to two or more output ports. The development for ultra-wideband (UWB) wireless

systems has presented a challenge to the design of wideband microwave circuits, including power divider. In addition to low insertion loss, the other important parameters to achieve include low amplitude ripple, high return loss, and high isolation over the entire frequency range.

T-junction power divider is the simplest power divider. To match the impedance of the output ports to the standard load impedance, a quarter-wave transformer is required. Due to the poor isolation and narrow bandwidth for return loss better than 15 dB, it is seldom used in modern microwave circuits.

E. J. Wilkinson overcomes the poor isolation issue by adding a resistor across output ports [1]. It was a major breakthrough in power divider design. The power divider, however, is only optimized at single frequency due to the limitation of the quarter-wave transformer. Since the line length is exactly quarter wavelength at the center frequency, the operating bandwidth of the power divider is limited in terms of return loss and isolation. Multiple quarter-wave transformers connected in cascade improve the bandwidth [2–4] at the cost of increasing the size of the circuit. However, ripples were observed in the transmission coefficient due to discontinuities at impedance steps. Many methods have been proposed to reduce the size but they come with some degradation of the electrical performances [5–13].

Several other modification works have been done on Wilkinson power divider to improve the operating bandwidth and isolation [14–21]. The design of Zhuanhong et al. [21] showed input return loss better than 15 dB over the frequency range of 3–18 GHz and amplitude ripple in the transmission coefficient was 0.4 dB peak-to-peak over the bandwidth in their circuit simulation results. However, the output return loss and isolation were poorer than 15 dB. Recently, a UWB power divider which exploits broadside coupling via multilayer slot configuration was introduced [22]. With an isolation resistor, the design could only achieve isolation in the range of 10–15 dB. The return loss could only be better than 10 dB for both input and output ports over the frequency range of 3.6–10.2 GHz.

In this paper, a better power divider with UWB performance is presented. The quarter-wave transformer in the conventional Wilkinson power divider is replaced by an exponentially tapered microstrip line. Since the tapered line provides a consistent impedance transformation across all frequencies [23], the amplitude ripple in the transmission coefficient and the input return loss is greatly improved. Additional resistors are added along the tapered line to improve the isolation and output return loss.
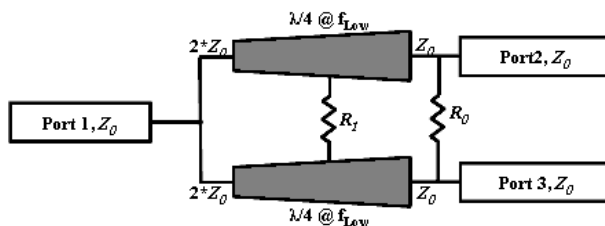
Figure 1. Tapered-line power divider design.

2. DESIGN AND ANALYSIS

Schematic diagram of the proposed power divider is shown in Fig. 1. The input port is connected with two symmetrical branches. Each branch comprises an exponentially-tapered microstrip line which transforms the impedance from 100 ohms to 50 ohms at the output port. Exponentially-tapered lines have the advantage of lower internal reflection and shorter line length compared to linear taper. The method proposed by Hecken [23] is used in the design of the tapered line because it has the advantage of avoiding discontinuities at the taper ends inherent in Klopfenstein's design [24]. Isolation resistor R_0 is mounted across the output ports, while the additional isolation resistors can be placed at suitable locations along the tapered line.

2.1. Design of Tapered-line

According to Hecken [23], the maximum input reflection of the tapered line can be determined using

$$|R(0)|_{\max} = \tanh \left[\frac{B}{\sinh B} (0.21723) \ln \left(\sqrt{\frac{Z_0(d)}{Z_0(0)}} \right) \right] \qquad (1)$$

where

    $Z_0(0)$ = Characteristic impedance at the input

    $Z_0(d)$ = Characteristic impedance at the output

The parameter B here will be used to determine the exponential taper curve of the transmission line. Larger values of B will result in a greater curve in the taper and lower reflection at the input. This is good but larger B may require longer transmission line to realize the desired return loss.

Upon selecting the value for B, the optimum characteristic impedance profile of the transmission line to minimize internal reflection is calculated using

$$\ln \frac{Z_0(z)}{Z_0(0)} = \frac{1}{2} \ln \frac{Z_0(d)}{Z_0(0)} \left\{ 1 + G\left[B, 2\left(\frac{z}{d} - 0.5\right)\right] \right\} \tag{2}$$

where

$Z_0(z) =$ Characteristic impedance of the line at position z.

$G(B, \xi) = \dfrac{B}{\sinh B} \displaystyle\int_0^{\xi} I_0\{B\sqrt{1 - \xi'^2}\}d\xi'$

$I_0(x) =$ modified Bessel function of the first kind (zero order)

Subsequently, the width profile of the tapered line can be calculated using a common microstrip synthesis formula.

2.2. Even Mode Analysis

When two equal amplitude and phase signals are applied to port 2 and 3 simultaneously, no current would flow through the isolation resistors. The even-mode equivalent circuit is as shown in Fig. 2. The isolation resistors are terminated with open circuit since no current flow through them. Thus, the isolation resistors can be omitted from this analysis.

The return loss of the tapered line is better than $|R(0)|_{\max}$ above the minimum frequency where the taper length is slightly longer than quarter wavelength. Nevertheless, it will transform 100 ohms at port 1 to 50 ohms at port 2 for all frequencies. Hence, a good input return loss and minimum ripple in the transmission coefficient can be achieved over a very wide frequency range.
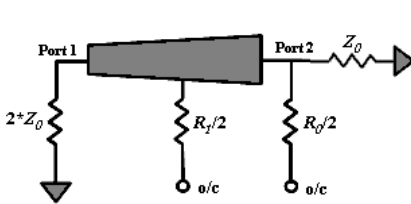

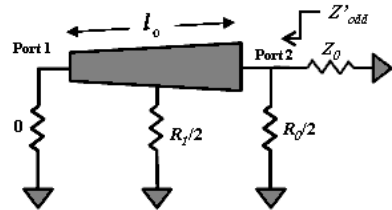**Figure 2.** Equivalent circuit for even mode.

Figure 3. Equivalent circuit for odd mode.

2.3. Odd Mode Analysis

Applying two equal amplitude but opposite phase signals to port 2 and 3 simultaneously will result in a voltage null at the mid-point of the isolation resistors. The odd-mode equivalent circuit is as shown in Fig. 3 where the isolation resistors and port 1 are grounded at mid-plane. Considering the case without R_1, the impedance matching performance will be the same as the conventional Wilkinson power divider. Short circuit at port 1 will be transformed to an open circuit when the tapered line is odd multiple of quarter wavelength. Port 2 will be perfectly matched when $Z'_{odd} = Z_0$ by choosing $R_0 = 2Z_0$. Simulation using CST Microwave Studio 3-D electromagnetic design software is performed for this design and also for conventional single-stage Wilkinson power divider. The same length of 29.65 mm is chosen for both the tapered line of this design and the quarter-wave transformer of conventional Wilkinson power divider (for board thickness of 0.508 mm and $\varepsilon_r = 2.2$). The simulation results in Fig. 4 show good isolation and output return loss at fundamental frequency and odd harmonics for both circuits. However, the tapered line design provides significant improvement on the amplitude ripple of the transmission coefficient as well as input return loss as shown in Fig. 5.

At even harmonics, the tapered line is multiple of half wavelength. Referring to Fig. 3, short circuit at port 1 will be transformed to short circuit at port 2. At second harmonic, voltage maximum of
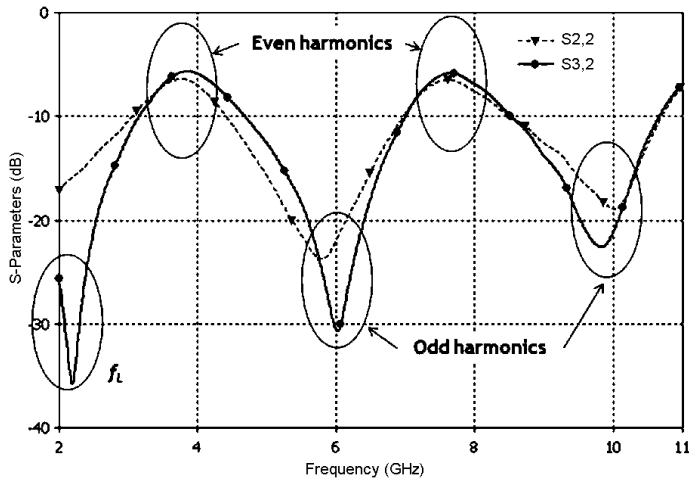

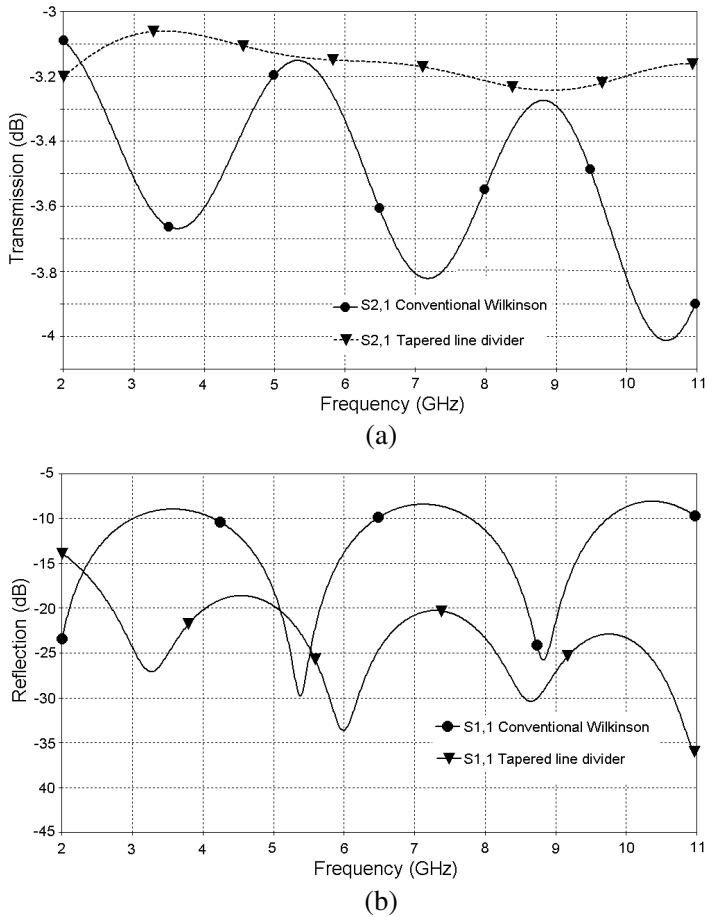**Figure 4.** Output return loss and isolation without R_1.

Figure 5. (a) Transmission coefficient and (b) input reflection of tapered-line divider without R_1 compared to conventional Wilkinson divider.

the standing wave occurs at mid-point of the tapered line. Adding a resistor R_1 will absorb the resonance. (The concept is similar to the use of resistive card at the center of rectangular waveguide attenuator where the electric field strength of TE_{10} mode is at its maximum.) Impedance matching can be re-established at both odd and even harmonics by optimizing the values of R_0 and R_1, giving rise to the improved isolation and output return loss better than 15 dB from 2 to 6.5 GHz as shown in Fig. 6.
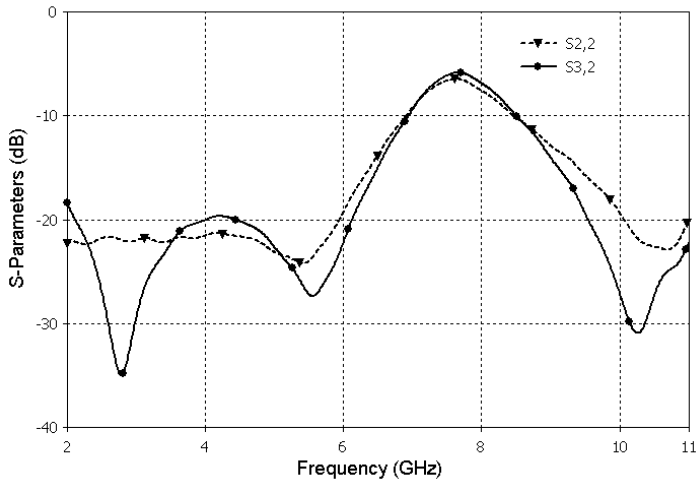
Figure 6. Output return loss and isolation with R_1 added at mid-point of the tapered line.

There will be two voltage maximum points along the tapered line at the fourth harmonic. Hence, two or more isolation resistors shall be added to the tapered line as shown in Fig. 7 to obtain UWB performance. The physical locations of R_1 and R_2 can be appropriately chosen. One may start by placing the resistors at equal spacing. The suitable values may be obtained by mean of an optimization method provided by CST Microwave Studio or other electromagnetic CAD software. Standard off-the-shelf values of R_0, R_1 and R_2 can be selected by further optimizing the physical locations to mount the resistors. More isolating resistors can be added to further enhance the performance if desired. As shown in the simulation results in Fig. 8, the isolation and output return loss can be better than 15 dB up to 10.2 GHz with 3 isolation resistors, to 13.6 GHz with 4 resistors, and 17.3 GHz with 5 resistors. The level of isolation and output return loss in the passband is also improved with more isolation resistors added. The transmission coefficient and input return loss are not affected because the isolation resistors only affect the odd mode and have no effect on the even mode.

3. EXPERIMENT RESULTS

Figure 9 shows the design of the UWB power divider. The length of the tapered line is 29.65 mm, built on 0.508-mm thick Rogers RT5880
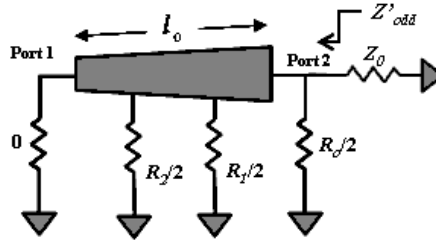
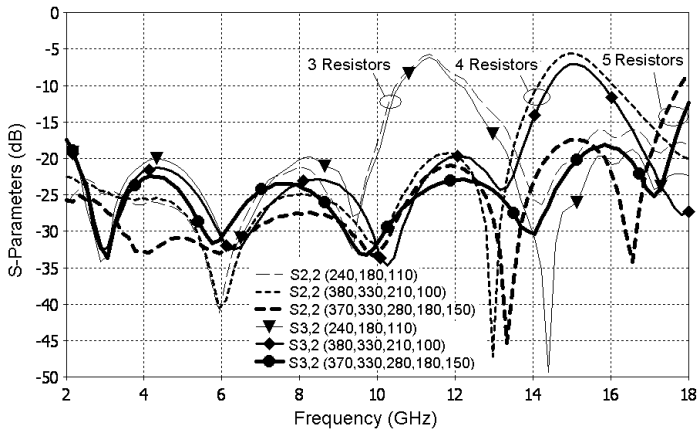**Figure 7.** Equivalent circuit for odd mode with multiple isolating resistors.

Figure 8. Output return loss and isolation with 3, 4 and 5 isolation resistors. The resistance values of $(R_0, R_1, R_2, \ldots)$ in ohms are given in the bracket.
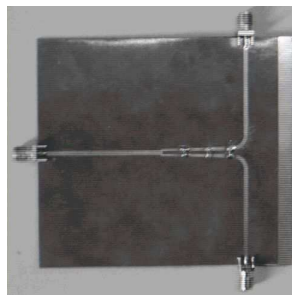

Figure 9. Physical layout of the tapered-line power divider.

board ($\varepsilon_r = 2.2$). In the design of the tapered line, $B = 5.5$ is selected such that the input reflection is better than 50 dB. The values of R_0, R_1 and R_2 are 240 Ω, 180 Ω and 110 Ω, respectively. The values and mounting locations are optimized using CST Microwave Studio.

Figure 10 compares the simulated and measured isolation performance of the proposed UWB power divider. Fig. 11 shows the return loss performance at port 1 and port 2. The isolation and return loss is better than 15 dB from 2 to 10.2 GHz. The measurement results generally match the simulation results. The differences are due to minor offset in soldering positions of the isolation resistors, hence the shift in the null points of the frequency response. Fig. 12 compares the simulated and measured transmission coefficient of the power divider. The peak-to-peak amplitude ripple is within 0.2 dB.

The simulation results of 3-section Wilkinson power divider based on Cohn method [2] are also shown in Figs. 10–12. The characteristic impedances of the quarterwave transformers are $Z_0 = 60.95$ Ω, $Z_1 = 70.71$ Ω, and $Z_2 = 82$ Ω, while the isolation resistances are $R_0 = 278$ Ω, $R_1 = 125$ Ω, and $R_2 = 130$ Ω (Z_0 and R_0 are closest to ports 2 and 3). The same substrate material is applied. The above values are selected such that the 3-section Wilkinson divider will provide the same bandwidth as the single-section tapered line divider proposed in this paper. While the input return loss, output return loss and isolation are comparable for the two designs, the 3-section Wilkinson
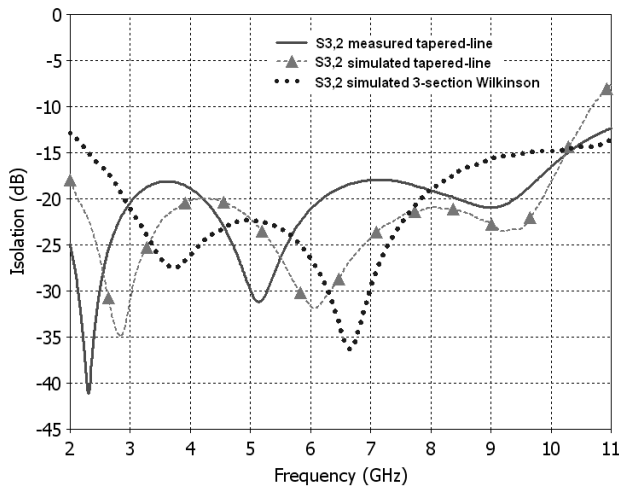

Figure 10. Simulated and measured isolation performance of the tapered-line divider compared with 3-section Wilkinson divider.
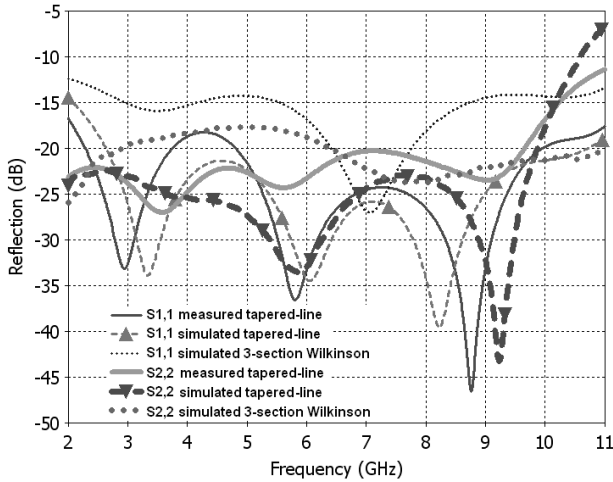
Figure 11. Simulated and measured return loss for port 1 and port 2 of the tapered-line divider compared with 3-section Wilkinson divider.
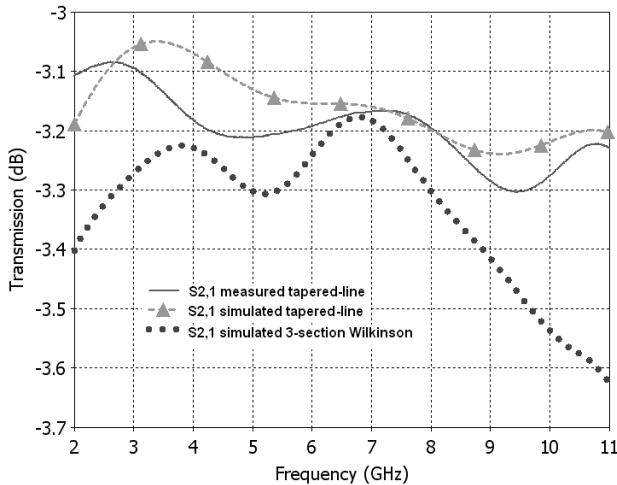

Figure 12. Simulated and measured transmission coefficient of the tapered-line divider compared with 3-section Wilkinson divider.

divider has a poorer amplitude ripple of 0.4 dB in the transmission coefficient. The ripple can be reduced by using other values of characteristic impedances and isolation resistances at the trade-off of narrower bandwidth due to the Chebyshev behavior of the design.

4. CONCLUSION

A UWB Wilkinson power divider has been designed. The use of exponential tapered line to replace the conventional quarter-wave transformer gives rise to very low amplitude ripple of 0.2 dB peak-to-peak in the transmission coefficient and superior input return loss better than 15 dB over an ultra-wide bandwidth from 2 to 10.2 GHz. Isolation and output return loss better than 15 dB are achieved over the same bandwidth by adding two isolation resistors along the tapered line. Standard off-the-shelf values of R_0, R_1 and R_2 can be selected by optimizing the physical locations to mount the resistors. Better performance can be achieved with more isolation resistors added. Hence, one may select the number of isolation resistors to be mounted based on the desired bandwidth and level of isolation and return loss specifications.

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