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Analysis and Design of Ultra-Wideband Unequal-Split Wilkinson Power Divider Using Tapered Lines Transformers

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Abstract An ultra-wideband unequal-split Wilkinson power divider with a 2:1 split ratio is presented. To achieve the ultra-wideband characteristics, the conventional quarter-wave arms of the divider are replaced by tapered lines. Moreover, two extra tapered transformers are incorporated at the output ports for matching purposes as the designed divider is of an unequal-split type. To obtain good isolation between the output ports, five isolation resistors are used, the values of which are determined using the simple odd-mode analysis of the Wilkinson power divider. For verification purposes, an ultra-wideband Wilkinson power divider that operates over a frequency range extending from 2 to 12 GHz is designed, simulated, fabricated, and measured. The results of the full-wave simulation and measurements verify the validity of the design procedure.

Keywords power divider, Wilkinson power divider, tapered lines, ultra-wideband

1. Introduction

There is an increased interest in the design of ultra-wideband (UWB) microwave components since the Federal Communication Commission’s approval to use the frequency range of 3.1 to 10.6 GHz for UWB applications, such as short-range indoor data transmission, microwave imaging, and through-the-wall radars. As a consequence, many researchers have recently been attracted to this field, and different microwave devices that support the use of the approved UWB frequency band have been presented. The microwave power divider is one of the key microwave components used in different wireless applications. They are extensively used in antenna feed networks, balanced mixers, and phase shifters. Thus, designing power dividers to be used in UWB systems is of utmost importance.
The Wilkinson power divider (WPD) is one of the dividers that gained a notable significance and interest in the literature related to the design of UWB dividers. For many applications, such as phase-array systems and beam-forming networks, power dividers with unequal power division ratios are required. Many configurations to build an unequal-split WPD have been investigated (Moradian & Oraizi, 2008; Li & Wang, 2011; Wu et al., 2008, 2009a; Zhu et al., 2010, Li et al., 2009a). In Moradian and Oraizi (2008), the application of the grooved substrate was presented for the design of a 4:1 unequal-split WPD. The grooves were applied along one of the divider strips that require high characteristic impedance for the purpose of overcoming its conventional narrow width. A stub-loaded transmission line was used in Li and Wang (2011) to design WPDs with arbitrary power division ratios. A WPD operating at a frequency and its first harmonic with an unequal power dividing ratio was proposed in Wu et al. (2008). To obtain the unequal power property, four groups of 1/6 wavelength transmission lines with different characteristic impedances were needed to match all ports. In Zhu et al. (2010), a shunt-stub WPD with a uniform impedance line was introduced. Compared with the conventional divider, the output distribution ratio was controlled by the length of the shunt stubs. A 10:1 unequal-split WPD was designed in Li et al. (2009a) by replacing the high-impedance line with two coupled lines terminated by two shorts. In Wu et al. (2009a), a WPD operating at an arbitrary dual-band with an unequal power dividing ratio was presented. The asymmetric structure that consists of seven sections of transmission lines with different characteristics impedances was given to achieve the unequal power division and matching characteristics. Furthermore, to obtain an acceptable isolation, a series resistor-inductor-capacitor structure was incorporated in the proposed design.

In this article, an UWB unequal-split WPD with a 2:1 split ratio is presented. The proposed device is aimed at covering the bands from 2 GHz to 12 GHz. Tapered-line transformers are incorporated in the proposed design. The design of those transformers is achieved using the even-mode analysis of the divider. To achieve acceptable output ports matching and isolation conditions, multiple resistors are mounted between the two tapered arms of the WPD. An optimization process is carried out to find the values of those uniformly distributed resistors considering the odd-mode analysis. It should be emphasized that the present article differs from Chiang and Chung (2010) in two aspects. First, an unequal-split WPD is considered here, while an equal-split WPD was investigated in Chiang and Chung (2010), and as a consequence, two different (asymmetric) microstrip tapered lines are considered in the WPD design. Furthermore, two extra tapered transformers are designed and incorporated at the power divider’s output ports for matching purposes. Second, in this study, the values of the shunt resistors are obtained through an independent optimization process using the odd-mode equivalent
circuit of the WPD, while in Chiang and Chung (2010), the built-in optimization tool in the full-wave simulator was used to find the resistors’ values.

2. Design of UWB 2:1 WPD

An outline of the proposed device is shown in Figure 1. Each branch of the conventional divider is replaced by a single microstrip tapered-line section. Since such tapered sections have almost constant input impedance across an extremely wide bandwidth, they are used to achieve the UWB operation of the WPD. In Section 2.1 (even-mode analysis), the design of the tapered lines is presented; while in Section 2.2 (odd-mode analysis), the values of the isolation resistors are derived.

2.1. Even-Mode Analysis

The even-mode equivalent circuits for the upper and lower branches of the proposed UWB divider are shown in Figure 2.

For an unequal-split WPD, $Z_{s1}$, $Z_{l1}$, $Z_{s2}$, and $Z_{l2}$ can be found using the following equations (Pozar, 2005):

\[
Z_{s1} = Z_0 \left( 1 + \frac{1}{k^2} \right), \quad (1a)
\]
\[
Z_{l1} = \frac{Z_0}{k}, \quad (1b)
\]
\[
Z_{s2} = Z_0 (1 + k^2), \quad (1c)
\]
\[
Z_{l2} = kZ_0, \quad (1d)
\]

where $k = \sqrt{P_2/P_3}$, and $P_2$ and $P_3$ are the output powers from ports 2 and 3, respectively.

Figure 2. Even-mode equivalent circuits for the UWB unequal-split WPD: (a) upper branch and (b) lower branch.
Hence, to obtain a 2:1 split ratio (i.e., \( k = \frac{\sqrt{2}}{} \)), and using a characteristic impedance \( Z_0 \) of 50 \( \Omega \), the values of \( Z_{s1} \), \( Z_{l1} \), \( Z_{s2} \), and \( Z_{l2} \) should be 75 \( \Omega \), 35.35 \( \Omega \), 150 \( \Omega \), and 70.71 \( \Omega \), respectively.

According to Chiang and Chung (2010) and Hecken (1972), the maximum input return loss (in dB) for a given tapered line used to match source impedance \( Z_s \) to load impedance \( Z_l \) is characterized by the following equation:

\[
|RL_{\text{input}}|_{\text{max}} = -20 \log \left[ \tanh \left( \frac{B}{\sinh B} (0.21723 \ln \left( \frac{Z_l}{Z_s} \right)) \right) \right],
\]

where \( B \) is a predefined design parameter used to determine the tapered line curve. It should be mentioned here that larger values of \( B \) result in lower reflection at the input port. However, increasing \( B \) will demand a wider tapered line width and longer length.

After choosing the value of \( B \) in order to achieve a desired input return loss, the exponential tapered line characteristic impedance is calculated using the following equation (Chiang & Chung, 2010; Hecken, 1972):

\[
\ln \left( \frac{Z(z)}{Z_s} \right) = 0.5 \ln \left( \frac{Z_l}{Z_s} \right) \left[ 1 + G(B, 2 \left( \frac{z}{d} - 0.5 \right)) \right],
\]

where

\[
G(B, \xi) = \frac{B}{\sinh B} \int_0^\xi I_0 \left( B \sqrt{1 - \xi'^2} \right) d\xi'.
\]

\( Z(z) \) in Eq. (3a) represents the characteristic impedance of the tapered line at point \( z \), and \( I_0(x) \) represents the modified zero-order Bessel function. The tapered line length \( d \) is a predefined variable chosen appropriately to achieve the desired maximum input return loss.

As noted above, the conventional quarter-wave transformers are replaced by their equivalent tapered-line transformers, considering \( (Z_{s1}, Z_{l1}) \) and \( (Z_{s2}, Z_{l2}) \), in order to achieve the UWB characteristics. Moreover, two extra tapered line transformers are designed to match the output ports to 50 \( \Omega \). The source and load impedances that are considered in the design of these matching tapered transformers are \( (Z_{l1}, Z_0) \) and \( (Z_{l2}, Z_0) \).

### 2.2. Odd-Mode Analysis

The odd-mode analysis is carried out to obtain the isolation resistors’ values needed to achieve the optimum output ports isolation and output ports matching conditions. Figure 3 shows the equivalent odd-mode circuit of the proposed divider (Qaroot et al., 2010).

First, each tapered line transformer will be subdivided into \( K \) uniform electrically short segments with length \( \Delta z = d/K \). The \( ABCD \) matrix for each section of the tapered line (considering the upper branch) shown in Figure 3 is calculated as follows (Pozar, 2005):

\[
\begin{bmatrix}
A & B \\
C & D
\end{bmatrix} = \begin{bmatrix}
A_1 & B_1 \\
C_1 & D_1
\end{bmatrix} \begin{bmatrix}
A_2 & B_2 \\
C_2 & D_2
\end{bmatrix} \cdots \begin{bmatrix}
A_i & B_i \\
C_i & D_i
\end{bmatrix}.
\]
Figure 3. Odd-mode equivalent circuit for the UWB unequal-split WPD.

where the $ABCD$ parameters of the $i$th segment are (Pozar, 2005)

$$A_i = D_i = \cos(\Delta \theta),$$

$$B_i = Z^2((i - 0.5)\Delta z)C_i = jZ((i - 0.5)\Delta z)\sin(\Delta \theta),$$

$$\Delta \theta = \frac{2\pi}{\lambda}\Delta z = \frac{2\pi}{c}f\sqrt{\varepsilon_{\text{eff}}}\Delta z.$$  

The effective dielectric constant $\varepsilon_{\text{eff}}$ of each section is calculated using the well-known microstrip line formula in Pozar (2005). Then, the total $ABCD$ matrix for the upper branch can be calculated as follows (Pozar, 2005):

$$[ABCD]_{\text{Total}} = [ABCD]_{R'_{N}} \cdot [ABCD]_{\text{first section}} \cdots$$

$$\cdot [ABCD]_{(N-1)th \text{ section}} [ABCD]_{R'_{N-1}} \cdot [ABCD]_{\text{Nth section}}.$$  

(6)

It is worth mentioning here that the isolation resistors are distributed uniformly (a resistor every $d/N$ distance, where $d$ is the tapered line length, and $N$ is the number of used resistors). Finally, and as illustrated in Figure 3, the following equation can be written:

$$\begin{bmatrix} V_1 \\ I_1 \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix}_{\text{Total}} \begin{bmatrix} V_2 \\ I_2 \end{bmatrix}.$$  

(7)

Setting $V_2 = 0$ leads to the following equation:

$$Z_{in}^0 = \frac{V_1}{I_1} = \frac{B}{D}.$$  

(8)
For perfect output port matching, the following condition should be satisfied:

\[ \Gamma_{out}(f_j) = \frac{Z_{in}^o(f_j) - Z_{in}}{Z_{in}^o(f_j) + Z_{in}} \]  

(9)

where \( f_j \) denotes the frequencies at which Eq. (9) is calculated. Here, a frequency increment of 1 GHz is used within the frequency range 2 to 12 GHz. So, for perfect output ports matching over the design frequency range, the following error function is considered (Shamaileh et al., 2011):

\[ \text{Error}_{out} = \sum_{j=1}^{M} |\Gamma_{out}(f_j)|^2. \]  

(10)

This optimization problem is solved using “fminunc.m” MATLAB routine (The MathWorks, Natick, Massachusetts, USA), where \( R'_1, \ldots, R'_N \) are the optimization variables to be determined. It should be noted here that the same procedure carried out in Eqs. (4) through (10) is repeated in order to obtain the optimum resistors’ values \( R''_1, \ldots, R''_N \), which minimize the output reflection for the lower branch in Figure 3. Finally, the overall resistance values can be calculated as follows (Qaroot et al., 2010):

\[ [R \quad R_2 \quad \cdots R_N] = [R'_1 \quad R'_2 \quad \cdots R'_N] + [R''_1 \quad R''_2 \quad \cdots R''_N]. \]  

(11)

3. Simulation and Experimental Results

Figure 4 represents the layout of the proposed UWB 2:1 WPD (without the isolation resistors). Considering a Roger RT5870 substrate (Rogers Corporation) with a relative permittivity of 2.33, a thickness of 0.508 mm, and a loss tangent of 0.0012, the lengths of each tapered WPD arm and output ports matching transformers needed to achieve an acceptable input/output ports matching conditions are set to 28 mm and 27 mm, respectively. Those lengths are approximately equal to the lengths of the conventional uniform quarter-wave transformers at 2 GHz. Besides, the design parameter \( B \) was set to 5.5, which corresponds to a maximum input return loss of 56.55 dB.

Figure 5 shows the effect of uniformly distributing three resistors (a resistor every 9.3 mm), four resistors (a resistor every 7 mm), and five resistors (a resistor every 5.6 mm) on the input/output ports matching parameters (\( S_{11}, S_{22}, \) and \( S_{33} \)), as well as the isolation between the two output ports (\( S_{23} \)). It should be pointed out here that the simulation results were obtained using the method of moments (MoM) based full-wave simulator.
IE3D (Mentor Graphics PCB Design Software, 2006). Moreover, the isolation resistors’ values in the three scenarios are obtained following the optimization procedure mentioned in Section 2.2. Table 1 shows the resulting resistors in each case.

It is clearly seen in Table 1 that the resistors’ values increase in magnitude in all cases but that of three resistors. This reflects the divergence of the optimization engine toward minimizing the error expressed in Eq. (10) when only three resistors are used.
Table 1

Optimized values of isolation resistors used in simulations of the 2:1 UWB WPD

<table>
<thead>
<tr>
<th>No. of resistors</th>
<th>$R_1$ (Ω)</th>
<th>$R_2$ (Ω)</th>
<th>$R_3$ (Ω)</th>
<th>$R_4$ (Ω)</th>
<th>$R_5$ (Ω)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Three resistors</td>
<td>22.34</td>
<td>651.41</td>
<td>428.765</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Four resistors</td>
<td>91.57</td>
<td>210.73</td>
<td>360.52</td>
<td>476.74</td>
<td>—</td>
</tr>
<tr>
<td>Five resistors</td>
<td>97.75</td>
<td>203.41</td>
<td>328.87</td>
<td>477</td>
<td>515.8</td>
</tr>
</tbody>
</table>

The error achieved when using three resistors was more than 0.9, which is considered very high as an output reflection coefficient, whereas the error is around 0.1 when using four and five resistors. The divergence in the three-resistor case was translated into the resistors’ variation listed in Table 1. Table 2 represents the error obtained in each case along with the obtained error value in both branches.

As shown in Figure 5, when using three resistors, an acceptable return loss (below 10 dB) at the input port and port 2 is achieved across the entire frequency range of interest. However, poor isolation and output return loss at port 3 are obtained at some frequency bands. On the other hand, better performance is clearly seen in the case of using four and five isolation resistors.

Figure 6 shows the simulated transmission parameters $S_{21}$ and $S_{31}$. Lower transmission loss is obtained in the case of using four and five resistors because of the optimal response achieved by the optimization engine in those two cases. In both scenarios, $S_{21}$ equals $-1.76$ dB ($\pm 0.8$ dB), while $S_{31}$ equals $-4.77$ dB ($\pm 1$ dB) over the frequency range of 2 to 12 GHz.

For verification purposes, the UWB unequal-split WPD with five isolation resistors is implemented over the same substrate previously mentioned. The practical surface-mount device (SMD) resistor values that are used in the fabrication are $R_1 = 100$Ω, $R_2 = 200$Ω, $R_3 = 330$Ω, $R_4 = 470$Ω, and $R_5 = 510$Ω. Figure 7 shows a photograph of the fabricated divider, while Figure 8 shows the simulated and measured scattering parameters.

As shown in Figure 8(a), both simulated and measured results show an acceptable input port matching (below $-10$ dB) over the frequency range of 2 to 12 GHz. Furthermore, the output ports matching parameters $S_{22}$ and $S_{33}$ are also below $-10$ dB over the same frequency range. Moreover, the simulations and the measurements results illustrated in Figure 8(b) show an acceptable isolation (below $-10$ dB) over the design frequency range. The simulation results for the transmission parameters are close to their theoretical values; $S_{21}$ is $-1.77$ dB ($\pm 0.5$ dB) in the frequency range of 2 to 12 GHz, and $S_{31}$ is

Table 2

Error values in the optimization as calculated from Eq. (10) for upper and lower branches of the device

<table>
<thead>
<tr>
<th>No. of resistors</th>
<th>Upper branch</th>
<th>Lower branch</th>
</tr>
</thead>
<tbody>
<tr>
<td>Three resistors</td>
<td>0.92</td>
<td>0.97</td>
</tr>
<tr>
<td>Four resistors</td>
<td>0.1</td>
<td>0.14</td>
</tr>
<tr>
<td>Five resistors</td>
<td>0.093</td>
<td>0.091</td>
</tr>
</tbody>
</table>
Figure 6. Transmission parameters $S_{21}$ and $S_{31}$ for the 2:1 UWB WPD with different numbers of isolation resistors. (color figure available online)

$-4.77$ dB ($\pm 1$ dB) over the same frequency range. The measured transmission parameters show acceptable characteristics except for a slight increase of the insertion losses at the upper end of the investigated band. That increase, as well as the discrepancies between the simulated and measured results is thought to be due to the connectors, the tolerance in the values of the five resistors, conductor and dielectric losses, and radiation losses.

Figure 9 shows the phase imbalance of the designed divider, which clearly illustrates an in-phase performance with less than $2^\circ$ imbalance over the entire frequency range that extends from 2 to 12 GHz. It is to be noted here that for applications that require compact

Figure 7. Photograph of the fabricated UWB 2:1 WPD with five isolation resistors. (color figure available online)
Figure 8. Simulated and measured scattering parameters for the fabricated UWB 2:1 WPD. (color figure available online)
Figure 9. Phase imbalance of the proposed UWB 2:1 WPD. (color figure available online)

4. Conclusions

The design of an UWB unequal-split WPD using tapered lines has been presented. The design of the UWB tapered lines is obtained from the even-mode analysis of the WPD, whereas the isolation resistors are calculated through an optimization process using the odd-mode equivalent circuit. Three scenarios are presented in such a way that the effect of using three, four, and five isolation resistors on enhancing the isolation between the two output ports, as well as achieving optimum output ports matching over the frequency range of 2 to 12 GHz, is studied. For verification purposes, an UWB unequal-split WPD, with a 2:1 split ratio, and five isolation resistors, is fabricated and measured. The good agreement between both simulation and measurement results and the design target proves the validity of the design procedure.

References


