Design and analysis of a 3-way unequal split ultra-wideband Wilkinson power divider

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In this article, a 3-way ultra-wideband (UWB) unequal split Wilkinson power divider (WPD) using tapered line transformers is presented. Three tapered lines are designed through the even-mode analysis, and used instead of the conventional 3-way WPD arms. In addition to the three main arms, three additional tapered transformers are used to match the output ports to the 50 Ω connectors. To achieve an acceptable output ports matching and isolation, multiple resistors are uniformly distributed and mounted between the three tapered arms of the WPD. An optimisation process is carried out to obtain the values of these resistors considering the odd-mode analysis. The proposed WPD is designed to operate over the frequency band of 2–12 GHz, and simulated using two full-wave EM simulators. Full-wave simulation and experimental results verify the design procedure.

Keywords: ultra-wideband; microstrip dividers; Wilkinson power divider; tapered lines

1. Introduction

Ultra-wideband (UWB) technology has the ability to find effective solutions for multiple problems in the radio system engineering and spectrum management, and many efforts have been proposed in the literature to meet the requirements that satisfy and improve the UWB characteristics for microwave power dividers/combiners (Abbosh 2007, 2012; Yao and Feng 2007; Wong and Zhu 2008; Yang and Chu 2008; Yang, Wang, and Fathy 2008; Zhang et al. 2009; Chiang and Chung 2010; Zhou, Wang, and Shen 2010a; Zhou, Wang, and Sheng 2010b; Chang et al. 2012; Hazeri 2012) like N-way Wilkinson power dividers (WPDs) that are widely used in front/end microwave subsystems, such as antenna arrays, and applications requiring antenna diversity. In Yang et al. (2008), a design of compact antenna arrays for UWB operation was presented, and a wideband WPD was used to compose the feed network. Tapered lines were incorporated in Chiang and Chung (2010) and Chang et al. (2012) to design two-way equal split UWB WPDs, where each arm of the conventional WPD was replaced by a tapered line transformer. In Chiang and Chung (2010), the values and locations of the isolation resistors were determined by the use of the built-in full-wave simulator optimisation engine. In Chang et al. (2012), the coarse grained
parallel micro-genetic algorithm was used to optimise the tapered line structure and the isolation resistors values. In Wong and Zhu (2008), an UWB WPD was designed using stepped impedance stubs in addition to parallel coupled lines at the output ports. In Yang and Chu (2008), UWB equal split WPD was designed to operate in the band extending from 3.1 to 10.6 GHz using two different cascaded transmission line transformers at each branch. A band notched UWB unequal split WPD was presented by Yao and Feng (2007), in which three cascaded sections were used to achieve the UWB characteristics. Defected ground structure (DGS) was incorporated in the WPD design to obtain the band rejection characteristics over specific frequency bands, whereas six resistors were used to achieve an acceptable isolation. Similarly, three cascaded transmission line transformers and a DGS were incorporated by Zhang et al. (2009) to design an equal split WPD with a band notch at the WLAN frequencies. Three resistors were used to satisfy the isolation between the two output ports. An UWB power divider based on overlapped butterfly open radial stub was proposed by Zhou et al. (2010a). The divider was designed by introducing one overlapped butterfly radial stub on each branch so that ultra-wideband performance was achievable. Delta stubs were incorporated in both WPD arms to achieve the UWB characteristics, as presented by Zhou et al. (2010b). Very recently, an equal-split 2-way WPD working in the frequency range 3.1–10.6 GHz UWB range has been proposed by Hazeri (2012). In Abbosh (2007, 2012), compact three way equal split power dividers were proposed using multilayer technology where in Abbosh (2007), the proposed divider utilised broadside coupling via multilayer microstrip/slot transitions of elliptical shape, while in Abbosh (2012), the proposed divider utilised broadside-coupled microstrip-coplanar waveguide structure.

In this article, and as an extension to what was reported in Chiang and Chung (2010), a planar 3-way UWB WPD is designed using tapered lines to achieve an operational band over a frequency range of 2–12 GHz. The proposed design differs from the one in Chiang and Chung (2010) in three major aspects: first, the WPD presented in Chiang and Chung (2010) had two output ports, while the one presented in this article has three output ports. Second, the proposed 3-way divider is of an unequal split type, in contrast to the one presented in Chiang and Chung (2010) in which equal power division was considered. Last but not least, the isolation resistors in the proposed design are uniformly distributed over the three main arms of the divider with their values being obtained through an optimisation process carried out after deriving the odd-mode design equations, while in Chiang and Chung (2010), such resistors’ locations and values were found by the built-in full-wave EM simulator’s optimisation engine.

2. Design of the 3-way UWB WPD

Figure 1(a) illustrates the layout of a single band, unequal split, three way conventional WPD, where $Z_{02}$, $Z_{03}$, and $Z_{04}$ are the characteristic impedances of the three uniform arms, and $k_n^2$ ($n = 1, 2, 3$) are the power splitting ratio constants (defined below), while Figure 1(b) represents the proposed 3-way, unequal split, tapered line-based UWB WPD, where each tapered line section has a varying characteristic impedance of $Z(z)$.

The characteristic impedances of the three main arms of the conventional WPD and the power splitting ratio constants can be found using the analysis presented in Qaroot and Dib (2010), in which the 2-way WPD is considered as the key starting point in analysing the 3-way divider. Firstly, to find $Z_{02}$, output ports 3 and 4 are combined together forming
a 2-way WPD with port 2 as the first output port, and $P' = P_3 + P_4$ as the second output port, with a power ratio constant of $k_1^2 = (P_3 + P_4)/P_2$. Secondly, to find $Z_{03}$, ports 2 and 4 are combined together forming another 2-way WPD, with port 3 as the first output port, and $P'' = P_2 + P_4$ as the second output port, with a power ratio constant of $k_2^2 = (P_2 + P_4)/P_3$. Finally, $Z_{04}$ can be found using the same procedure, by combining ports 2 and 3 resulting in a 2-way WPD with port 4 as the first output port, and $P''' = P_2 + P_3$ as the second output port, with a power ratio constant of $k_3^2 = (P_2 + P_3)/P_4$. Based on the above analysis, the characteristic impedances $Z_{02}$, $Z_{03}$, and $Z_{04}$ are found using the following equations (Pozar 2005):

$$Z_{02} = Z_0 \sqrt{k_1 \times (1 + k_1^2)} \quad \text{(1a)}$$

$$Z_{03} = Z_0 \sqrt{k_2 \times (1 + k_2^2)} \quad \text{(1b)}$$

$$Z_{04} = Z_0 \sqrt{k_3 \times (1 + k_3^2)} \quad \text{(1c)}$$

Using the even-mode analysis presented in Pozar (2005), the output port of the $M$th arm is matched as shown in Figure 2.
Now, to obtain the UWB behaviour, each uniform section in Figure 1(a) is replaced by a tapered line as shown in Figure 1(b). The maximum input return loss for any tapered line that matches a source impedance of $Z_s$ to a load impedance $Z_l$ can be calculated using the following formula (Chiang and Chung 2010):

$$|RL_{\text{input}}|_{\text{Max}} = -20 \log \left( \tanh \left( \frac{B}{\sinh(B)} \right) \left( 0.21723 \ln \left( \frac{Z_l}{Z_s} \right) \right) \right)$$  (2)

where $B$ is a predefined design parameter used to determine the tapered line curve. It should be pointed out here that larger values of $B$ result in lower reflection at the input port. However, increasing $B$ will demand wider tapered line width and longer length. In this design, $B$ will be chosen to achieve a specific return loss. The tapered line characteristic impedance can be found using the following equation (Chiang and Chung 2010):

$$\ln \left( \frac{Z(z)}{Z_s} \right) = 0.5 \ln \left( \frac{Z_l}{Z_s} \right) \left( 1 + G(B, 2 \left( \frac{z}{d} - 0.5 \right) \right)$$  (3a)

where

$$G(B, \xi) = \frac{B}{\sinh(B)} \int_{0}^{\xi} I_0 \left( B \sqrt{1 - \xi^2} \right) d\xi'$$  (3b)

$Z(z)$ 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.

In order to obtain an acceptable output port matching and isolation, four resistors are uniformly distributed and mounted between every two adjacent arms. The odd-mode analysis is carried out to obtain the values of these resistors similar to the approach described in Shamaileh, Qaroot, Dib, and Sheta (2011). Figure 3 shows the odd-mode analysis of the proposed WPD, where $R^o_m$ is the $m$th optimised resistor using the odd-mode analysis for the $m$th arm (Shamaileh et al. 2011). In order to start the analysis, each tapered line is subdivided into $K$ uniform electrically short segments, each of $\Delta z = d/K$ in length. These segments are uniformly distributed into $N$ sections, and each section is with $K/N$ segments group, where the number of sections equals the number of isolation resistors. The $ABCD$ matrix of the $i$th segment is given as follows (Khalaj 2008):

$$A_i = D_i = \cos(\Delta \theta)$$  (4a)

$$B_i = j Z \left( \left( i - \frac{1}{2} \right) \Delta z \right) \times \sin(\Delta \theta)$$  (4b)

$$C_i = \frac{j}{Z \left( \left( i - \frac{1}{2} \right) \Delta z \right)} \times \sin(\Delta \theta)$$  (4c)

where $\Delta \theta = \frac{2\pi}{\lambda} \times \Delta z = \frac{2\pi f}{c} \sqrt{\varepsilon_{\text{eff}}} \times \Delta z$. 
The $ABCD$ matrix of each section of the tapered line can be obtained as follows (Pozar 2005):

$$
egin{bmatrix}
A & B \\
C & D
\end{bmatrix} = 
\begin{bmatrix}
A_1 & B_1 \\
C_1 & D_1
\end{bmatrix} 
\begin{bmatrix}
A_2 & B_2 \\
C_2 & D_2
\end{bmatrix} \cdots \cdots 
\begin{bmatrix}
A_{K/N} & B_{K/N} \\
C_{K/N} & D_{K/N}
\end{bmatrix}
$$

(5)
The total \( ABCD \) matrix of the \( M \)th tapered line is calculated as follows (Pozar 2005):

\[
\begin{bmatrix} A & B \\ C & D \end{bmatrix}^{\text{Total}} = \left( \begin{bmatrix} A & B \\ C & D \end{bmatrix}^{\text{Section 1}} \right)^{M} \cdots \left( \begin{bmatrix} A & B \\ C & D \end{bmatrix}^{\text{Section N}} \right)^{M}
\]

Then, the following equation can be considered (Pozar 2005):

\[
\begin{bmatrix} V_1 \\ -I_1 \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} V_2 \\ -I_2 \end{bmatrix}
\]

Setting \( V_2 = 0 \) leads to:

\[
\frac{V_1}{I_1} = \frac{B}{D} = Z_{\text{in}}
\]

Perfect output ports matching is achieved by minimising the following error function (Shamaileh et al. 2011):

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

where

\[
\Gamma_{\text{out}}(f_j) = \frac{Z_{\text{in}}^0(f_j) - Z_{IM}}{Z_{\text{in}}^0(f_j) + Z_{IM}}
\]

where \( Z_{IM} = Z_0k_M \), \( f_j \) are the frequencies at which the above equations are calculated. Here, a frequency increment of 1 GHz is used within the frequency range 2–12 GHz. Finally, the isolation resistors between arms 1 and 2 are (Pozar 2005; Shamaileh et al. 2011):

\[
[R_1 R_2 \ldots R_N] = [R_1^1 R_2^1 \ldots R_N^1] + [R_1^2 R_2^2 \ldots R_N^2]
\]

The same procedure is carried out to find the isolation resistors between arms 2 and 3.

3. Example

As an example, a 3-way UWB WPD with power splitting ratios of 40% for port 2 and 30% for each of ports 3 and 4 is designed. Considering a reference impedance of 50 \( \Omega \), a Rogers RT/duriod 5870 substrate with \( \varepsilon_r = 2.33 \), loss tangent of 0.0012, and a thickness of 0.508 mm, the design parameters are found to be: \( Z_{02} = 87.5 \Omega \), and \( Z_{04} = 112.83 \Omega \). \( B \) is chosen to be 5.3, resulting in a maximum input return loss of 55 dB. The length of each tapered arm is chosen to be 27.5 mm, 28 mm and 28 mm for the upper, middle and lower branches, respectively. These lengths are approximately \( \lambda/4 \) at the lowest frequency (2 GHz). Four resistors are used (a resistor every 7 mm) between the adjacent arms to achieve an acceptable isolation between the output ports. Figure 4 shows the layout of the designed WPD with extra three tapered line transformers used for matching purposes. The matching transformers’ characteristic impedances are: \( Z_{T1} = \sqrt{50 \times 61.24} = 55.33 \), \( Z_{T2} = \sqrt{50 \times 76.38} = 61.8 \), and \( Z_{T3} = \sqrt{50 \times 76.38} = 61.8 \), each with a length of 27 mm. Using the even mode analysis, the source and load impedances for the main arms are \( Z_{s1} = 125 \Omega \), \( Z_{l1} = 61.23 \Omega \), \( Z_{s2} = Z_{s3} = 166.67 \Omega \), and \( Z_{l2} = Z_{l3} = 76.38 \Omega \).
The values of the isolation resistors are found to be: 617.8 V, 450 V, 279.5 V and 120 V between points (1, 5), (2, 6), (3, 7) and (4, 8), respectively. Besides, resistors’ values of 708 V, 493.8 V, 322.7 V, and 130 V are placed between points (5, 9), (6, 10), (7, 11) and (8, 12), respectively. The proposed UWB WPD is simulated using the method of moments-based IE3D (www.zeland.com, 2006) and the finite element method-based HFSS (HFSS: High Frequency Structure Simulation based on Finite Element Method, V. 10) simulators. The simulated $S$-parameters are shown in Figure 5.

As shown in Figure 5, the input and output ports matching parameters, and the isolation parameters are lower than $-10$ dB over the entire band of interest (2–12 GHz). The insertion loss parameters $S_{21}$, $S_{31}$ and $S_{41}$ are around $-4$ dB, $-5.5$ dB and $-5.5$ dB, respectively, which are almost equal to their theoretical values of $-3.98$ dB, $-5.23$ dB and $-5.23$ dB. The slight discrepancies between the theoretical and simulated results,
especially at higher frequencies, are thought to be due to the coupling between the arms, since the arms are designed close to each other in order to connect the chip resistors.

4. Measurements

The designed UWB, 3-way WPD has been fabricated and measured using an Anritsu Vector Network Analyzer 37369C. A picture for the fabricated UWB, 3-way WPD is shown in Figure 6, where surface mount resistors are used. The measured S-parameters are shown in Figure 7. In general, measured results show good agreement with the simulated ones where the input matching S-parameter ($S_{11}$) is below $-10$ dB over the frequency range of interest except around 11 GHz. The measured output ports matching S-parameters ($S_{22}$, $S_{33}$ and $S_{44}$) verify the simulated ones. The measured insertion loss S-parameters values are close to the simulated ones especially at lower frequencies; the differences at higher frequencies are due to the fact that the dielectric loss is a function of frequency. The isolation between the output ports is very good as shown in the measured isolation S-parameters ($S_{23}$, $S_{24}$, and $S_{34}$) although approximate resistors (depending on the available resistors) were used instead of the exact optimised resistors. In the fabricated UWB WPD, short pads were used to identify the exact location of the isolation resistors, which increases the coupling effects between adjacent arms. Also, the dispersive behaviour of the dielectric losses and the accuracy of the connectors soldering and resistors placing, which were performed by hand, contribute in increasing the losses. These factors, in addition to the connectors and cables losses, justify the slight discrepancies between the simulated and measured S-parameters, specially the transmission S-parameters $S_{21}$, $S_{31}$, and $S_{41}$.

5. Conclusions

In this article, a 3-way, unequal split, UWB, tapered line-based WPD is proposed, where tapered line transformers are incorporated to achieve the UWB characteristics.
The proposed divider is designed to operate in the band extending from 2–12 GHz. In addition to the three tapered line-based main arms, three output matching transformers are designed to match the output ports to 50 \Omega connectors. Isolation between the output ports is accomplished using four resistors mounted in planar mode between adjacent arms. Odd-mode analysis is carried out to find the optimal values of these resistors. Simulated and measured $S$-parameters are in good agreement with theoretical ones which validates the design procedure.

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**References**


