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Theoretical design and implementation of equal and unequal split ultra-wide band Wilkinson power divider with Chebyshev impedance transform

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In this study, we designed multi-section UWB Wilkinson power dividers for both equal and unequal power divider. The key innovation is successfully matching these power dividers using the Chebyshev method. The proposed method achieves very low insertion losses and high transmission coefficients across the ports. For the three-section equal power divider, Chebyshev polynomials were used to model the reflection coefficient, and the characteristic impedance for each section was calculated symmetrically. The design achieved a fractional bandwidth of 106% for a 20 dB return loss, with an insertion loss of 0.3 dB. For unequal multi-section dividers, power division ratios of 1.5:1 and 2:1 were chosen. Theoretical microwave calculations were used to determine the input and output transmission line impedances. Chebyshev approximation was then applied to design the three-section unequal power dividers. The return losses for these unequal dividers were measured at 17 dB and 15 dB, with fractional bandwidths of 120% and 126%. Both circuits had insertion losses of 0.25 dB. The consistent results from analytical calculations, simulations, and measurements confirm the effectiveness of the Chebyshev method for both equal and unequal power division.

Keywords: Wilkinson power divider, Chebyshev impedance matching, unequal power division, ultra-wide band impedance matching, multi section WPD

1 Introduction

In microwave technique, the circuit ports must be matched with the line impedance throughout the bandwidth (BW) in which the circuits operate. In many applications, the output ports of the circuits are tried to be matched to the impedance of $50 + j0\ \Omega$ [1]. Otherwise, impedance mismatch will occur as the characteristic impedance of any of the source, transmission line and load will be different from each other. The power carried by the electromagnetic wave coming to the transmission line will be reflected back (Γ) due to this mismatching and not all of it will be transmitted [2]. To eliminate this incompatibility, impedance matching techniques are used in microwave circuits [3, 4]. In microwave transmission lines, ultra-wide band (UWB) impedance matching processes are generally performed with real impedance values by using lines of quarter wavelength from the input point.

Wilkinson power divider (WPD) is microwave circuits that divide the input power equally (or not) as much as the number of output ways, with no loss or very low loss when the output ports are matched. Conventional WPDs use a transmission line with a quarter wavelength of the selected center frequency in impedance matching [2]. In order to operate in a wide frequency range, the impedance matching applied on the WPD output branches must be broadband. For UWB matching, multi-section transmission lines or hybrid matching topologies are generally preferred. Until recently, many UWB and multi-section impedance matching techniques have been studied on WPDs [5-7].

The advantage of multi-section impedance matching technique over single section in WPD design is that the characteristic impedance of the sections can be chosen arbitrarily with the help of any pattern [6, 8-10]. These patterns can be selected from functions that can be modeled mathematically on reflection and transmission coefficients. As a result of the pattern or optimization calculations used, larger bandwidth, lower return loss (RL), transmission (IL) and isolation (IS) losses can be obtained in multi-section WPD designs [7, 11-13].

WPD circuits, which have two outputs with equal ways, divide the input power equally to symmetrical output arms and transmit 50% to each branch [2, 14, 15]. Unequal way WPDs allow the power to be split up between the ways at desired rates [8, 16-19]. In the unequal way WPD design, the characteristic impedances seen from the input and output of the ways are determined according to a selected power division ratio. Then, according to the input and output impedance values of the branches, the characteristic impedance of each section in each way is calculated with the help of UWB approximations [8, 20, 21]. In microwave circuits, the line width corresponding to the characteristic impedance value of the transmission lines can be calculated according to the substrate material used.

In this study, the application of Chebyshev impedance matching technique to multi-section equal and

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unequal way WPDs has been studied. The novelty of the article is the demonstration that the Chebyshev method can be used in equal and unequal power division.

In the second part, the general schematic of the application of multi-section matching techniques on WPD has been given and the UWB approach has been mentioned. Modeling of Chebyshev impedance transform as reflection coefficient has been explained. The design and realization of the three-section equal way UWB WPD has been analyzed together with simulation and experimental results. In the third section, general schematic of unequal way multi-section WPDs and its odd-even mode analysis have been studied. Theoretical calculations of input and output impedances have been made in the multi-section power division process. Two unequal way WPD implementations with a division ratio of 1.5:1 and 2:1 have been applied. Three-sections Chebyshev method has been applied on these two WPDs. Then, characteristic impedance of each section on each way of WPDs has been determined.

In order to show the bandwidth and matching success of the designs modelled analytically, simulation and measurement results have been compared. Results obtained from the study have been compared with previous studies. WPD simulations have been modeled in the ADS 2009 program. In all measurements of scattering parameters of fabricated circuits, Rohde Schwarz FSH6 spectrum analyzer has been used as a vector network analyzer with tracking generator. In the fourth part, the study has been summarized and its originality has been mentioned.

2 Multi-section UWB WPD and Chebyshev impedance transform

WPD circuits with two outputs (T junction) with equal branches, divide the input power equally to the output ways and allowing half of the power to be transmitted to each. Logarithmically, the transmitted power corresponds to –3 dB in each way [2].

Since the length or line width of each section is proportional to the impedance value at different frequencies, multi-section designs allow it to operate in a wider relative (fractional) frequency range ($\Delta f/f_0$). It is known that as the number of layers increases, the bandwidth increases [21, 22] .

Figure 1 shows the general scheme of equal way multi-section WPD design. Each section length is a quarter wavelength ($\theta = \lambda/4$). of the selected center frequency (f_0). The line thicknesses Z_1, Z_2, Z_3 representing the characteristic impedances of the transmission lines on the branches are different from each other. The thicknesses of the opposing lines on equal ways are the same ($Z_1{}' = Z_1$, $Z_2{}' = Z_2$ and $Z_3{}' = Z_3$). By determining the characteristic impedances of the sections with various mathematical patterns and optimization techniques, power division can be performed in a wider frequency range [3].

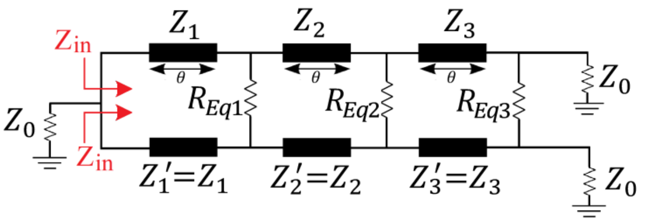


Fig. 1. General schematic of equal way multi-section WPD design

R_{Eqn} (n=1,2,3) isolation resistors between sections are calculated from odd-even mode analysis. In Odd mode calculation, the input is short-circuited. Short-circuited at one end, $R_{Eqn}/2$ resistors are placed at the ends of the sections. The odd mode equivalent circuit of the equal way multi-section WPD design is shown in Fig. 2a. In Even mode calculation, the intersections of the layers are open circuit (OC). Since both outputs are equal split, the source impedance calculation seen at the input is $2xZ_0$ [2]. Figure 2b shows the even mode equivalent circuit model. The transmission line of each section is added one after the other without resistor.

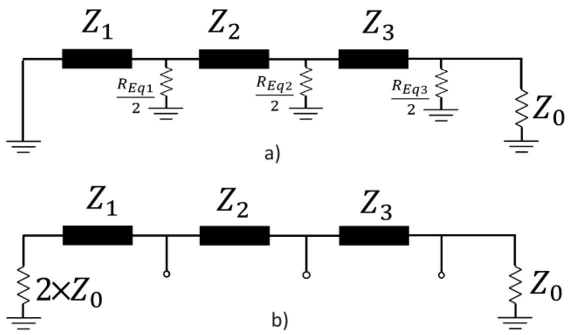


Fig. 2. Equivalent circuit of the equal way multi-section WPD a) odd mode b) even mode

2.1 Chebyshev multi-section impedance transform

The Chebyshev impedance transformer has been chosen while determining the characteristic impedance of the sections on the branches in the multi-section WPD design. This matching technique uses Chebyshev polynomials while calculating the matching sections [23]. Modeling of impedance matching according to Chebyshev polynomials has been given in (1)

$$T_N(\sec\theta_m) = \frac{1}{\Gamma_m}\left|\frac{Z_L - Z_0}{Z_L + Z_0}\right| \approx \frac{1}{2\Gamma_m}\left|\ln\frac{Z_L}{Z_0}\right| \quad (1)$$

where, θ_m is the angle calculated for a tolerable reflection coefficient Γ_m. Z_L represents the load impedance and Z_0 represents the characteristic impedance of the transmission line. In general, the Chebyshev transform can be found in Eqn. (2) by adapting the N^{th} degree Chebyshev polynomial to the reflection coefficient of $T_N(\sec\theta)$ [1].

$$\Gamma(\theta) = A.e^{-jN\theta}T_N(\sec\theta_m\cos\theta) \quad (2)$$

Here, θ is the line angle. The line angle is the angle to which the quarter wavelength corresponds. A is the design coefficient. It is a parameter given its first A value in (3). A is calculated individually for each section [21].

$$A = \frac{Z_1 - Z_0}{Z_1 + Z_0}\frac{1}{T_N(\sec\theta_m)} \quad (3)$$

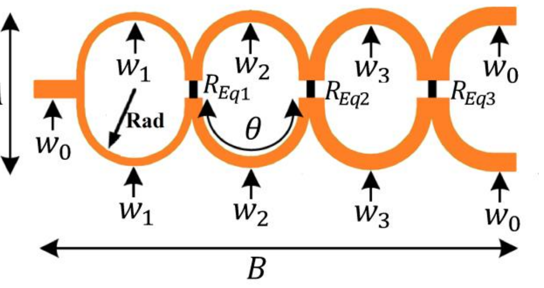
The reflection coefficient Γ_n and impedance Z_n of each section in the Chebyshev impedance transformer depend on the values of the previous sections. Although the bandwidth is high in this matching technique, there are some disadvantages. One disadvantage is that it is computed on an acceptable reflection of Γ_m. In other words, some tolerance is shown against reflection. Another disadvantage is the ripple in the reflection-frequency graph. However, it is a design that can achieve lower reflection performance and bandwidth compared to single and other multi-section impedance matching techniques [2].

2.2 Application of Chebyshev method to equal way WPD

$Z_0 = 50\,\Omega$ has been chosen in the WPD design that divides the input power into two equal ways. For $N = 3$ section Chebyshev matching, the impedance of each section has been mathematically calculated according to [21]. Since $Z_{in} = 100\,\Omega$ is seen when looking at each output from the input port, Chebyshev matching has been made to align 100 Ω to 50 Ω. The accepted reflection level has been chosen as logarithmic as $\Gamma_m = -20$ dB. Analytically calculated $Z_1 = 87.8\,\Omega$, $Z_2 = 67.9\,\Omega$ and $Z_3 = 55.5\,\Omega$

Arlon AD300D substrate material has been used for the designed WPD circuit. Dielectric permittivity is $\epsilon_r = 2.94$ and tangential loss is $\tan\delta = 0.002$. The thickness of the material whose underside is completely covered with a copper (ground) surface is $h = 0.76$ mm. The thickness of the copper on the top and bottom surface of the WPD is $t = 0.035$ mm. Considering these properties, transmission line widths of the characteristic impedances of Z_0, Z_1, Z_2 and Z_3 have been calculated as $w_0 = 1.93$ mm, $w_1 = 0.7$ mm, $w_2 = 1.16$ mm, $w_3 = 1.64$ mm respectively. The center frequency of the design has been selected as $f_0 = 2.45$ GHz to include more application bands. Quarter wavelength in AD300D material is $\lambda_{guided}/4 = 20$ mm. Calculating wavelength according to the permittivity and height of the substrate materials is quite common in microwaves. Each section has been bent in a semicircle to make the branches take up less space and reduce size. Radius is 6.32 mm. The outer dimensions of the circuit are $A = 18$ mm and $B = 54$ mm.

In order for the WPD circuit to perform power division without loss or with little loss, the odd-even mode analysis at the center frequency has been made according to [21]. The isolation resistors between the output branches have been calculated as $R_{\mathrm{Eq1}} = 166\,\Omega$, $R_{\mathrm{Eq2}} = 226\,\Omega$ and $R_{\mathrm{Eq3}} = 227\,\Omega$. In Fig. 3, the dimensions and lengths of the Chebyshev matched equal way WPD circuit and its manufactured version can be seen.



a)

b)

Fig. 3. Equal way multi-section WPD: a) dimensions, b) manufactured version of the circuit

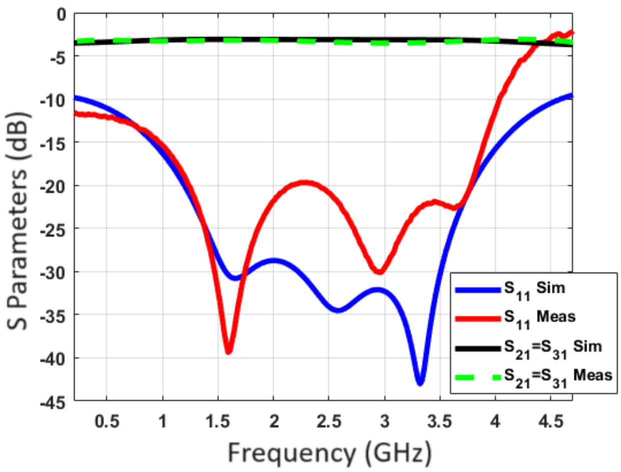


Fig. 4. S_{11}, S_{21} and S_{31} parameters of the equal way WPD

In the equal way WPD circuit, return loss and output return losses (S_{11}, $S_{22} = S_{33}$) are below 20 dB, and the bandwidth is BW = 1.20 to 3.80 GHz. At these frequencies, the percent fractional bandwidth has been calculated as BW = 106%. Theoretically, in an equal way WPD circuit, the output powers are $S_{21} = S_{31} \cong -3$ dB of the power transmitted from the input way [1]. Insertion Loss (IL) in non-ideal circuits can be obtained by subtracting -3 dB from the transmitted power [21, 24]. Figure 4 shows the graphics of RL and IL by frequency. In equal way WPD circuit, IL = 0.3 dB in both simulation and measurement.

The isolation (IS) parameter, which evaluates the effects of the output ports from each other, has been realized as $IS \geq 20$ dB in the simulation and measurement results for the equal way WPD. Figure 5 shows the graph of output return losses ($S_{22} = S_{33}$) and IS (S_{32}) parameters vs. frequency.

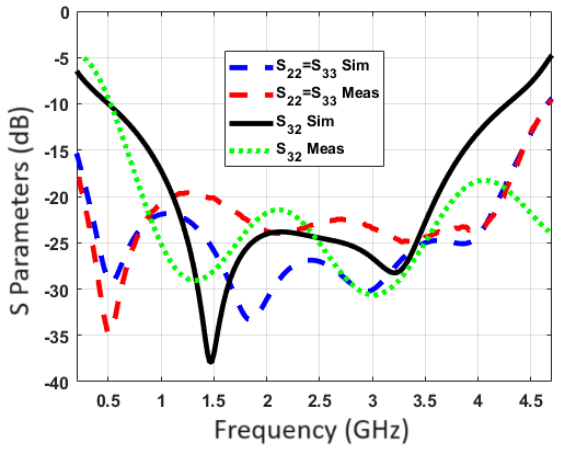


Fig. 5. S_{22}, S_{33} and S_{32} parameters of the equal way WPD

3 Unequal way multi-section WPD design

For unequal power dividers split the input power (P_1) to two unequal output ways (P_2 and P_3). Theoretically, in unequal way WPDs, the ratio of powers to each other is defined as the dividing factor (k^2). The division factor is given in (4) [8, 25].

$$k^2 = \frac{P_3}{P_2}\ , \qquad k^2 \in \mathbb{R}^+ \tag{4}$$

All WPDs with unequal output meet the $k^2 \neq 1$ condition. In multi-section impedance matching techniques, while power division is calculated, the line impedance of the output way is calculated individually for each section. Here, the sections on the transmission line on P_2 are expressed in $Z_i{}'$ in Eqn. (5) and those on P_3 in $Z_i{}''$ in Eqn. (6) ($i = 0, 1, 2$ or 3) [8].

$$Z_i{}' = Z_i\sqrt{k(1+k^2)} \tag{5}$$

$$Z_i{}'' = Z_i/k^2 \tag{6}$$

In Fig. 6, the general schematic of the unequal way WPD has been given. The calculation of the isolation resistors R_{Un}, ($n = 1, 2$ or 3) between the branches can be determined by odd-even mode analysis of all ways individually, unlike the equal way WPD. In odd mode, resistors with a short circuit at one end are placed on each path. As seen in (7) the sums of these oppose resistors give the odd mode resistor calculation ($R_{Un_{odd}}$). The odd mode equivalent circuit of the unequal WPD design is shown in Fig. 7.

$$R_{Un_{odd}} = Z_n{}'\sqrt{k^2} + Z_n{}''/\sqrt{k^2} \tag{7}$$

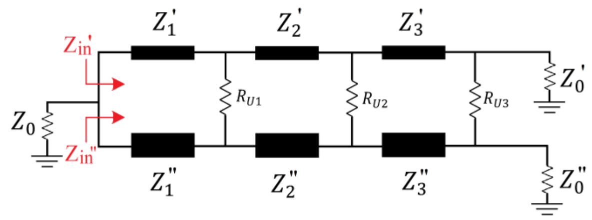


Fig. 6. General schematic of unequal way multi-section WPD design.

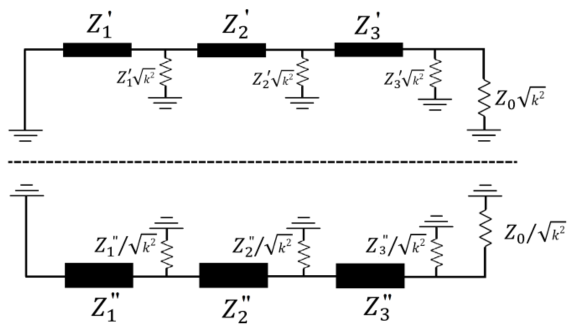


Fig. 7. Odd mode Equiwalent circuit of unequal way multi-section WPD design

In the even mode calculation, each resistor between the sections becomes an open circuit (OC). Since it is unequal split for two separate outputs, source and load characteristic impedance calculations seen at the input and output are calculated individually for each path [2]. Figure 8 shows the even mode equivalent circuit model of the unequal way WPD. Transmission line of each section has been added one after another without resistors.

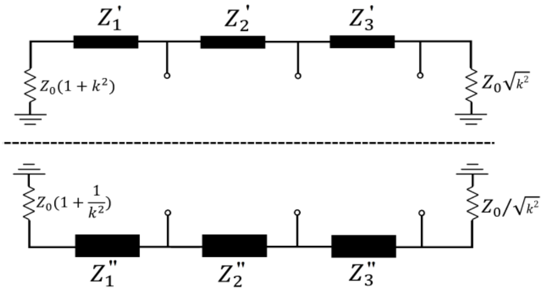


Fig. 8. Even mode equivalent circuit of unequal way multi-section WPD design

In this study, the following two different dividing factors (k^2) have been selected in multi-section unequal way WPD designs. In addition, the impedances of the ports have been calculated. In the case where the input and output impedances of the ports are known, a multi-section Chebyshev impedance transform has been applied and the characteristic impedances of the sections on each way have been determined. Thus, the UWB application of unequal power division has been realized.

3.1 Division factor 1.5:1 *power divider design and implementation*

In this application, $k^2 = P_3/P_2 = 1.5$ has been selected in this WPD circuit that separates the input power into two unequal ways. Therefore, 40% of the power will be transferred to Port 2 through the second way and 60% to Port 3 through the third way.

Three-section Chebyshev matching has been applied to both ways individually and the impedance of each section has been calculated. When looking at the output way of P_2 from the input port, $Z_{in}' = 125\ \Omega$ and the output impedance $Z_0' = 61.23\ \Omega$ seen from Port 2 are seen. Chebyshev transform has been matched 125 Ω to 61.23 Ω. Similarly, when looking at the output way of P_3 from the input port, $Z_{in}'' = 83.33\ \Omega$ and the output impedance of $Z_0'' = 40.82\ \Omega$ has been seen from Port 2. Using Chebyshev matching, 83.33 Ω has been matched to 40.82 Ω. In the Chebyshev method, the tolerable reflection coefficient level has been chosen as logarithmic $\Gamma_m = -20$ dB As a result of analytical calculations $Z_1' = 102\ \Omega$, $Z_2' = 85.30\ \Omega$, $Z_3' = 73.06\ \Omega$ $Z_1'' = 68\ \Omega$, $Z_2'' = 57.33\ \Omega$ and $Z_3'' = 48.70\ \Omega$.

Just like equal way WPD, the Arlon AD300D substrate material has been used in unequal way WPD circuits. The center frequency of the design has been selected $f_0 = 2.45$ GHz. The transmission line lengths of the sections and the radius of the semicircular bended lines are also the same.

Odd-even mode analysis of the proposed 1.5:1 WPD circuit has been done as stated above. Isolation resistors have been calculated as $R_{U1} = 180\ \Omega$, $R_{U2} = 151\ \Omega$ and $R_{U3} = 130$. In Fig. 9, the dimensions and lengths of the Chebyshev matched 1.5:1 unequal way WPD and the manufactured version of the circuit can be seen. Transmission line widths have been calculated as $w_0 = 1.93$ mm, $w_4 = 0.49$ mm, $w_5 = 0.74$ mm $w_6 = 1$, $w_7 = 1.39$ mm, $w_8 = 1.16$ mm, $w_9 = 1.55$ mm $w_{10} = 2$ and $w_{11} = 2.69$ mm.

Although return loss and output return losses (S_{11}, S_{22} and S_{33}) have been calculated analytically for 20 dB in the 1.5:1 unequal way WPD circuit, they performed $RL \geq 17$ dB in measurement and simulation. The bandwidth is between 0.85 and 3.80 GHz. In this range, the fractional bandwidth has been calculated as $BW = 120\%$. Isolation has been realized as $IS \geq 18$ dB. Figure 10 shows the graph S_{11} and S_{32} parameters of 1.5:1 unequal way WPD according to frequency.

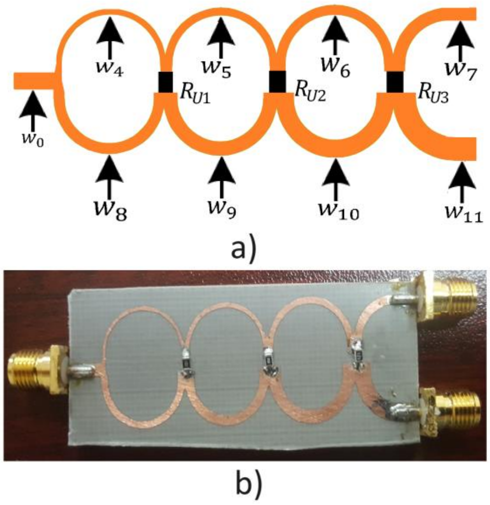


Fig. 9. 1.5:1 unequal way multi-section WPD: a) dimensions b) manufactured view of the circuit

Theoretically, $S_{21} \approx -4$ dB power can be transmitted in the second way, which divides the power into 40%. As a result of the measurement and simulation, this value almost has been overlapped with the theoretical calculation. There is a loss of $IL \approx 0.25$ dB in this way. Likewise, $S_{31} \approx -2.21$ dB power can be transferred on the third way that divides the power into 60%. Here, according to the measurement and simulation results, there is a loss of $IL \approx 0.25$ dB between analytical calculations. When insertion losses are subtracted, approximately 37.7% of the power from the second way and 57.4% from the third way can be transferred along the BW. In Figures 11 and 12, a graph of 1.5:1 unequal way WPD's S_{21}, S_{31}, S_{22} and S_{33} parameters have been given according to frequency.

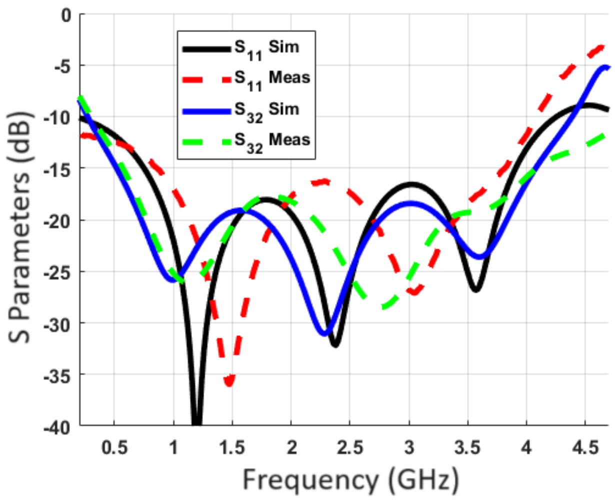


Fig. 10. S_{11} and S_{32} parameters of the 1.5:1 unequal way WPD

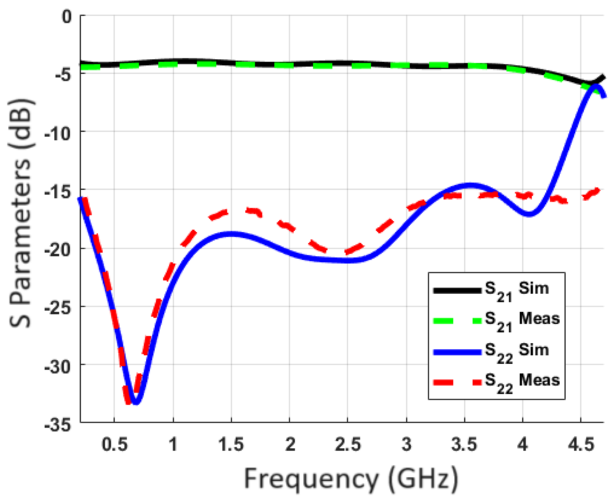


Fig. 11. S_{21} and S_{22} parameters of the 1.5:1 unequal way WPD

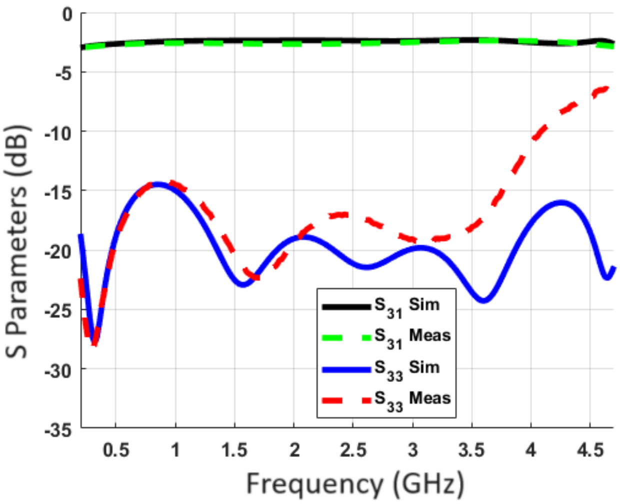


Fig. 12. S_{31} and S_{33} parameters of the 1.5:1 unequal way WPD

3.2 Division factor 2:1 *power divider design and implementation*

In this last WPD application that divide the input power into two unequal ways, $k^2 = P_3/P_2 = 2$ has been selected. Therefore, 33.3% of the power will be transferred to Port 2 through the second way and 66.6% to Port 3 through the third way.

Three-section Chebyshev matching has been applied individually in both ways. The impedance of each section has been mathematically calculated. When looking at the output way of P_2 from the input port, $Z_{in}{}' = 150\ \Omega$ and the output impedance $Z_0{}' = 70.71\ \Omega$ seen from Port 2 are seen. Chebyshev transform have been matched 150 Ω to 70.71 Ω. Similarly, when looking at the output way of P_3 from the input port, $Z_{in}{}'' = 75\ \Omega$ and the output impedance of $Z_0{}'' = 35.35\ \Omega$ has been seen from Port 2. Using Chebyshev matching, 75 Ω has been matched to 35.35 Ω. Chebyshev method, the acceptable reflection coefficient level has been chosen as logarithmic $\Gamma_m = -20$ dB As a result of analytical calculations $Z_1{}' = 121.20\ \Omega$, $Z_2{}' = 101.40\ \Omega$, $Z_3{}' = 84.80\ \Omega$ $Z_1{}'' = 60.60\ \Omega$, $Z_2{}'' = 50.70\ \Omega$ and $Z_3{}'' = 42.40\ \Omega$.

In the proposed 2:1 WPD circuit, isolation resistors have been calculated as $R_{U4} = 214\ \Omega$, $R_{U5} = 180\ \Omega$ and $R_{U6} = 150\ \Omega$. In Fig. 13, dimensions and lengths of the Chebyshev matched 2:1 unequal way WPD and the manufactured version of the circuit can be seen. Here, transmission line widths have been calculated as $w_0 = 1.93$ mm, $w_{12} = 0.32$ mm, $w_{13} = 0.50$ mm $w_{14} = 0.75$, $w_{15} = 1.08$ mm, $w_{16} = 1.42$ mm, $w_{17} = 1.9$ mm $w_{18} = 2.48$ and $w_{19} = 3.20$ mm.

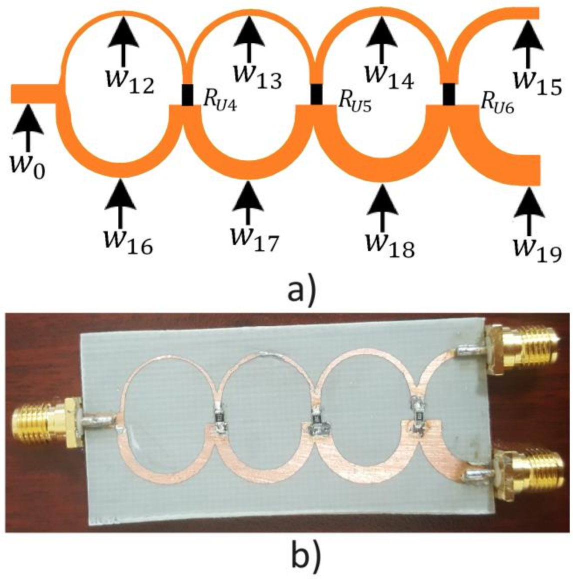


Fig. 13. 2:1 unequal way multi-section WPD: a) dimensions, b) manufactured view of the circuit

Return and output return losses (S_{11}, S_{22} and S_{33}) have been calculated analytically for 20 dB in the designed 2:1 unequal way WPD. However, return losses performed at $RL \geq 15$ dB. The bandwidth is $BW = 0.80$ to 3.90 GHz. At these frequencies, its fractional width has been calculated as $BW = 126.5\%$. Isolation has been realized as $IS \geq 15$ dB. Figure 14 shows the graph of S_{11} and S_{32} parameters of 2:1 unequal way WPD according to frequency.

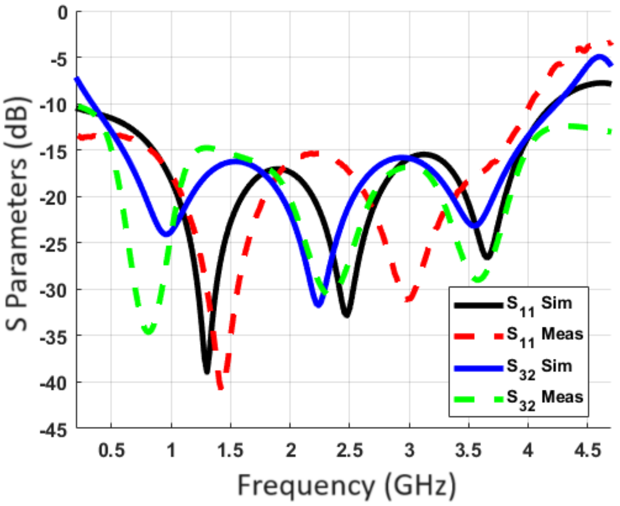


Fig. 14. S_{11} and S_{32} parameters of the 2:1 unequal way WPD

Theoretically, $S_{21} \approx -4.77$ dB power can be transferred in the second way, which divides the power as 33.3%. There is a loss of $IL \approx 0.25$ dB in this way. Likewise, $S_{31} \approx -1.76$ dB power can be transferred on the third way, which divides the power as 66.6%. Here, there is a loss of $IL \approx 0.25$ dB between the measurement and simulation results and the analytical calculation. When the losses have been removed, approximately 31.1% of the power from the second way and 63% from the third way can be transferred along the BW. In Figures 15 and 16, the graph of the 2:1 unequal way WPD's S_{21}, S_{31}, S_{22} and S_{33} parameters have been shown according to frequency.

In this study, Chebyshev impedance matching technique has been applied to dividing factors $k^2 = 1.5$ and $k^2 = 2$ WPDs with three-section equal and unequal ways. The performance of the proposed technique has been evaluated over scattering parameters and frequency. The technique applied on WPDs designed as UWB has been successful in all multi-section circuits. The performances of the circuits have been realized very close to each other in theoretical, measurement and simulation techniques. The fact that the technique applied on more than one equal or unequal circuit, calculation, simulation and experimental results almost overlap with each other proves the validity and accuracy of the technique. In Tab. 1, the performances of RL, IL, IS and operational-fractional bandwidth parameters of the equal way WPD have been given in comparison with previous studies. In Tab. 2, the performances of RL, IL, IS and operational-fractional bandwidth parameters of unequal way WPD circuits have been given in comparison with similar studies in the literature.

Table 1. Comparison of the equal Chebyshev WPD with previous equal way WPD studies

Ref.	Method	f_0 (GHz)	RL (dB)	IL (dB)	Op. Band (GHz)	% BW ($\Delta f / f_0$)	WPD division
[9]	Microstrip balun-quadrature coupler	*	11	1.3	0.7-2.5	*	Equal
[11]	Segmented structure	0.56	20	0.47	0.2-0.8	100	Equal
[15]	Gysel power divider	6	15	1	4.0-8.2	63	Equal
[10]	Coplanar waveguide balun	2	15	0.8	0.80-3.20	*	Equal
This work	**Chebyshev impedance transform**	**2.45**	**20**	**0.3**	**1.20-3.80**	**106**	**Equal**

* not mentioned or calculated in the study

Table 2. Comparison of the unequal Chebyshev WPD with previous unequal way WPD studies

Ref.	Method	f_0 (GHz)	RL (dB)	IL (dB)	Op. band (GHz)	% BW ($\Delta f/f_0$)	Dividing rate
[17]	Isolation improvement	4	20	1	2.20-5.30	83	3:1
[19]	Size reduction	0.8 & 2.0	-20	0.1 & 0.3	0.711-0.980 & 1.89-2.09	*	3:2 & 2:1
[8]	Optimize each section	1.0	-15	0.2 & 0.5	*	110	2:1
[18]	Trantanella	1.4	15	*	0.75-2.05	*	2.73:1
[16]	Non-uniform transmission line	*	10	1	3.10-10.60	*	2:1& 3:1
This work	**Chebyshev impedance transform**	**2.45**	**17**	**0.25**	**0.85-3.80**	**120**	**1.5:1**
This work	**Chebyshev impedance transform**	**2.45**	**15**	**0.25**	**0.80-3.90**	**126**	**2:1**

* not mentioned or calculated in the study

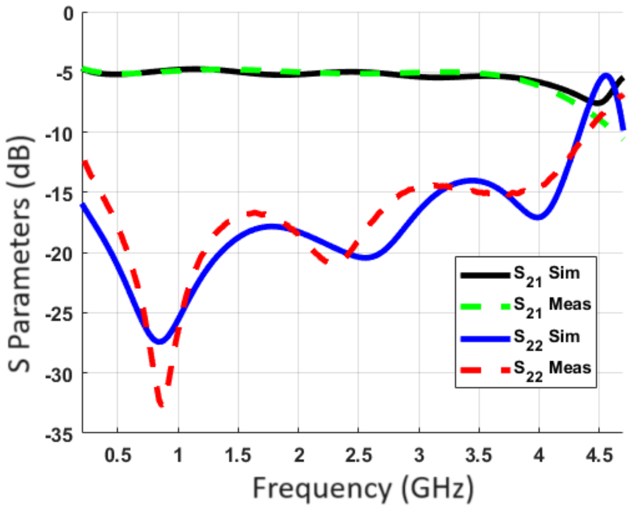


Fig. 15. S_{21} and S_{22} parameters of the 2:1 unequal way WPD

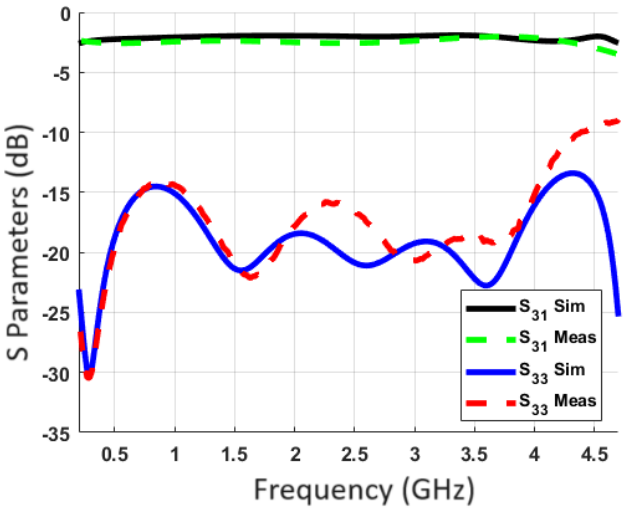


Fig. 16. S_{31} and S_{33} parameters of the 2:1 unequal way WPD

Tables 1 and 2 show that the Chebyshev impedance transform technique is more successful in UWB WPD than other patterns and approximations in the literature. Besides, since the frequencies at which the circuits operate cover many microwave communication bands, it can be said that their usability in microwave applications is high.

4 Conclusions

In this study, multi-section equal and unequal way UWB WPD circuits have been designed. Chebyshev impedance matching method has been applied to WPD circuits. The novelty of this study is the application of Chebyshev impedance matching method to equal and unequal way WPDs.

Chebyshev polynomials have been modeled as reflection coefficients for equal way multi-section WPD. Then, characteristic impedance of each section in symmetrical ways has been calculated. The power division factors of unequal multi-section WPD output ways have been selected as $k^2 = 1.5$ ($P_2 = 40\%$ and $P_3 = 60\%$), $k^2 = 2$ ($P_2 = 33\%$ and $P_3 = 66\%$). Analytically, the input and output impedances of unequal ways have determined by basic microwave calculations. Then, by applying Chebyshev approximations to all these ways, three-section unequal way WPD circuits have been designed. Isolation resistors in all circuits have been calculated by odd-even mode analysis. Center frequency has been selected as 2.45 GHz in all proposed circuits.

The performances of WPDs have been evaluated according to transmission, reflection, isolation and fractional bandwidth. In the Chebyshev approach, the tolerable return loss threshold has been chosen as 20 dB in the equal division WPD. In addition, return losses in simulation and measurement results in unequal circuits have been realized as 17 and 15 dB, respectively. In all circuits, insertion losses are very low and power transmission from the ports is quite high.

The operational bandwidths of the proposed multi-section WPDs are $BW_{Eq} = 1.20$ to 3.80 GHz in equal way WPD, $BW_{1.5:1} = 0.85$ to 3.80 GHz in unequal 1.5:1 WPD and $BW_{2:1} = 0.80$ to 3.90 GHz in WPD with a power split ratio of 2:1. Fractional band widths have been as 106%, 120% and 126%, respectively.

Analytical and simulation calculations and fabrication measurements have overlapped results in the UWB frequency range in equal and unequal power division circuits. Therefore, it has been proved that the Chebyshev method is applicable on equal and unequal multi-section power dividers.

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