Jordanian Journal of Computers and Information Technology (JJCIT), Vol. 06, No. 03, September 2020.

N- WAY COMPACT ULTRA-WIDE BAND EQUAL AND UNEQUAL SPLIT TAPERED TRANSMISSION LINES WILKINSON POWER DIVIDER

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(Received: 27-May-2020, Revised: 15-Jul.-2020, Accepted: 3-Aug.-2020)

ABSTRACT

In this article, compact N-way Ultra Wide Band (UWB) equal and unequal split Wilkinson Power Dividers (WPDs) using exponentially λ/4 Tapered Transmission Line Transformers (TTLTs) are designed. First, 2-way WPDs are designed, simulated and then cascaded to get 4-way (equal and unequal split) and 8-way (equal split) UWB WPDs. 2- and 4-way (equal and unequal split) WPDs are fabricated and tested. The simulated and measured results of all the designed dividers are good in terms of insertion, return losses and group delay through UWB frequency band. The analysis of these dividers is carried out using the commercial ANSYS High Frequency Structure Simulator (HFSS) software package which is based on the Finite Element Method (FEM). Moreover, A MATLAB built-in function "fmincon.m" is used to find the optimum values of the three resistors chosen for perfect isolation. To validate the results, the simulation results are compared with the measured ones.

KEYWORDS

Ultrawide band (UWB), Wilkinson power divider (WPD), Tapered transmission lines (TTLs), N–way WPD, HFSS.

1. INTRODUCTION

Ultra-wideband (UWB) wireless communication is a revolutionary wireless technology that provides excellent opportunities in the modern wireless communication system due to its special characteristics, such as low cost, high data rate, small physical size and less power consumption [1]. In 2002, the unlicensed use of UWB frequency band (3.1 GHz - 10.6 GHz) was authorized by Federal Communications Commission (FCC) with a restriction on transmit power level to -41.3 dBm/ MHz, avoiding the interference with the coexisting narrow band frequency technologies, such as Wireless Fidelity (WiFi) operating under different rules that share the same bandwidth within the UWB frequency range. Each radio channel in UWB has more than 500 MHz or 20% bandwidth, depending on its centre frequency [2]. The special characteristics of UWB technology make it more beneficial in many applications, such as in military, security, civilian commerce and medicine [3]-[4]. Power dividers are essential devices that enable the RF power to be divided or combined within an environment and they are widely used in many wireless communication applications, such as antenna diversity, radar applications, antenna feeders and frequency discriminators [5]. Wilkinson Power Divider (WPD) is the most commonly used divider and it was proposed to overcome the matching and isolation problems of T-junction power dividers. Since WPD generally provides narrow band, many efforts were done to make it suitable for the recent requirements in UWB wireless communication applications. In [6], a compact UWB WPD was proposed using only one section based on exponentially λ/4 TTLTs. One stepped-impedance open-circuited, overlapped butterfly radial and delta stub was added to each branch of WPD to increase the bandwidth (UWB) in [7]. Two-section Uniform Transmission Line Transformers (UTLTs) and TTLTs were used to design UWB WPD with an equal split ratio in [8]-[9]. UWB WPD with four sections of circular bending shape (TLTs) optimized based on micro-Genetic Algorithm (micro-GA) was proposed in [10]. Authors in [11] designed UWB WPD using binomial multi-section matching transformer. Taper equation in [6] was used to design 2- and 3-way unequal split UWB WPD in [12] and [13], respectively. UWB 3:1 WPD was proposed in [14] using two sections of Asymmetric Coupled Transmission Lines (ACTLs) and one section of two different length TTLs. UWB WPD with

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improved Fractional Bandwidth (FBW) was obtained in [15] by adding a circular stub and an L-type parasitic short line. Recently, Chebyshev type bandpass filtering UWB (1 GHz -5 GHz) equal split WPD using 5-section transformers with Short Circuited Stubs (SCSs) was designed in [16] based on synthesis theory, where the number and positions of stubs are controlled. UWB WPD can be also integrated with tuneable Band Pass Filters (BPFs) [17]-[18] to switch between UWB and other coexisting narrow bands in multiband communication system to reduce its size (instead of using multiple antennas).

In this paper, a compact UWB WPD is designed based on the technique used in [6]. N-way WPDs are mostly used as a feeding network to antenna arrays at different frequency bands [19]-[22]. In this work, 2-way, 4-way (equal and unequal split) and 8-way equal split UWB WPDs are designed using TTLTs in Sections 2, 3 and 4, respectively. Finally, Section 5 demonstrates the conclusion of this work. The simulation in this paper is carried out using ANSYS High Frequency Structure Simulator (HFSS) software package.

2. COMPACT 2-WAY TTLS UWB WPD

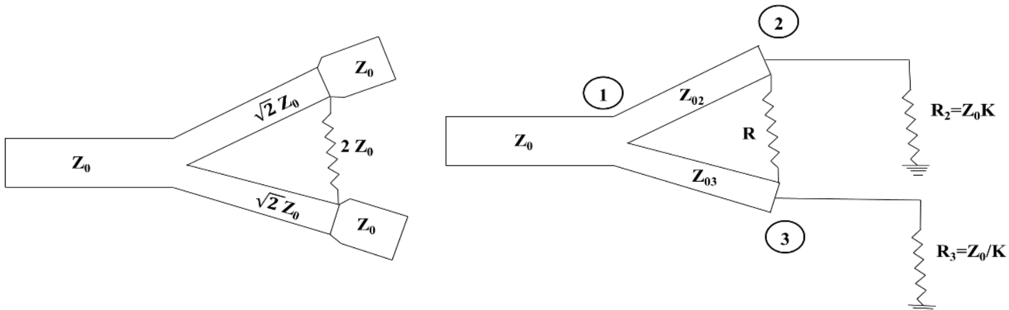
In the conventional equal split microstrip WPD, as shown in Figure 1a, the feeding port is connected to two parallel λ/4 Uniform Transmission Line Transformers (UTLTs) with a characteristic impedance of $\sqrt{2}$ Z_0. The output ports are terminated with a microstrip transmission line having the same impedance as the line connecting the feeding port. The output ports are decoupled *via* a resistor R that equals 2 Z_0. Unequal split microstrip WPD is used in the design of a microwave distribution network to reduce the complexity of using a broadband coupler with a phase shifter. Unequal split power division is achieved if the impedances of λ/4 UTLTs are different from each other, as shown in Figure 1b. Furthermore, the second section of the quarter-wave transformers is needed to bring the arm impedance back to 50 Ω (this section is not included in Figure 1b for simplicity). In this figure, Z_{02} and Z_{03} are the characteristic impedances of the upper and lower arms, respectively. Here, $K^2 = P_3/P_2$ is the power splitting ratio between output ports 2 and 3 and $R = R'+R''$ is the isolation resistor between them. According to [5] ,

$$Z_{02} = K^2 Z_{03}\sqrt{K(1+K^2)} \tag{1.1}$$

$$Z_{03} = Z_0\sqrt{\frac{1+K^2}{K^3}} \tag{1.2}$$

$$R = R' + R'' = \frac{Z_0(1+K^2)}{K} \tag{1.3}$$

where $R' = KZ_0$and $R'' = \frac{Z_0}{K}$



(a) (b)

Figure 1. WPD (a) Equal split (b) Unequal split.

Based on [6], each λ/4 UTLT in the equal-split and 2:1 unequal split WPD was replaced by its equivalent TTLT based on the optimum characteristic impedance profile of the transmission line:

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

where Z_S and Z_L are the source and load impedances and d is the λ/4 TTL;

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

where $I_0(x)$ is the modified Bessel function of the first kind (zero order). B is a parameter chosen to minimize the internal return loss which is given by:

$$|R|_{max} = tanh\left[\frac{B}{sinh(B)}\,(0.21723)ln\left(\sqrt{\frac{Z_L}{Z_S}}\right)\right] \tag{3}$$

As B increases, lower input reflection is obtained; however, this will lead to a wide transmission line. So, B is selected to obtain a suitable return loss with a reasonable transmission line width. Here, B is selected to be 5.

Take in consideration that the operating frequency in this work is selected to be 3.1 GHz and the chosen substrate material is Rogers RO4003C with εr= 3.55, height h = 0.813 mm and dielectric loss tangent of 0.0027. Table 1 shows the dividers' design parameters**.** To find the optimum values of the three resistors in both equal and unequal split WPDs, the optimization process in [23] is applied. In this process, a MATLAB built-in function called "fmincon" is used, in which the transmission line of length d is divided into L sections according to the number of the required resistors. As the number of resistors increases, perfect isolation is achieved. In this work, three isolation resistors are chosen. Each tapered line is subdivided into M uniform short sections of length $\Delta z = d/M$. Then, each L section has M/L subdivisions. Odd analysis is used to find the required isolation resistors for equal-split UWB TTLWPD, as illustrated in Figure 2, where Z_{L2} and Z_{L3} are the load impedances of ports 2 and 3, respectively and Z_{in} is the input impedance looking into the output port**.**

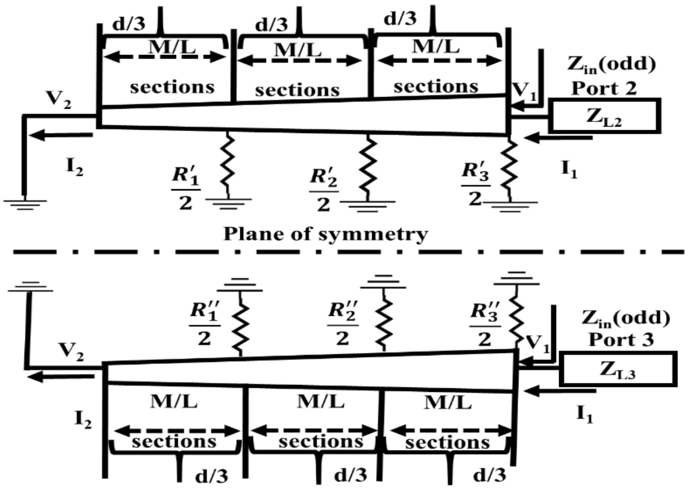


Figure 2. Odd-mode equivalent circuit for equal-split UWB TTLWPD.

To find the values of R_1, R_2 and R_3 and for perfect matching at the output, the following error function should be minimized *via* 'fmincon' function:

$$Error_{out}= \max\,(E_{f_1}^{out}, E_{f_2}^{out}, \dots, E_{fm}^{out}) \tag{4}$$

where f_j (j = 1, 2, ….m) are the frequencies in UWB frequency band with Δf = 0.5 GHz and

$$E_{fj}^{out} = \left|\Gamma_{out}(f_j)\right|^2 \tag{4.a}$$

$$\Gamma_{out}(f_j) = \frac{Z_{in}^{o}\,(f_j)-Z_o}{Z_{in}^{o}\,(f_j)+Z_o} \tag{4.b}$$

And from Figure 2, $\frac{V_1}{I_1} = \frac{B}{D} = Z_{in}^{o}$; by setting $V_2 = 0$ and solving:

$$\begin{bmatrix} V_1 \\ I_1 \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix}_{Total} \cdot \begin{bmatrix} V_2 \\ I_2 \end{bmatrix} \tag{5}$$

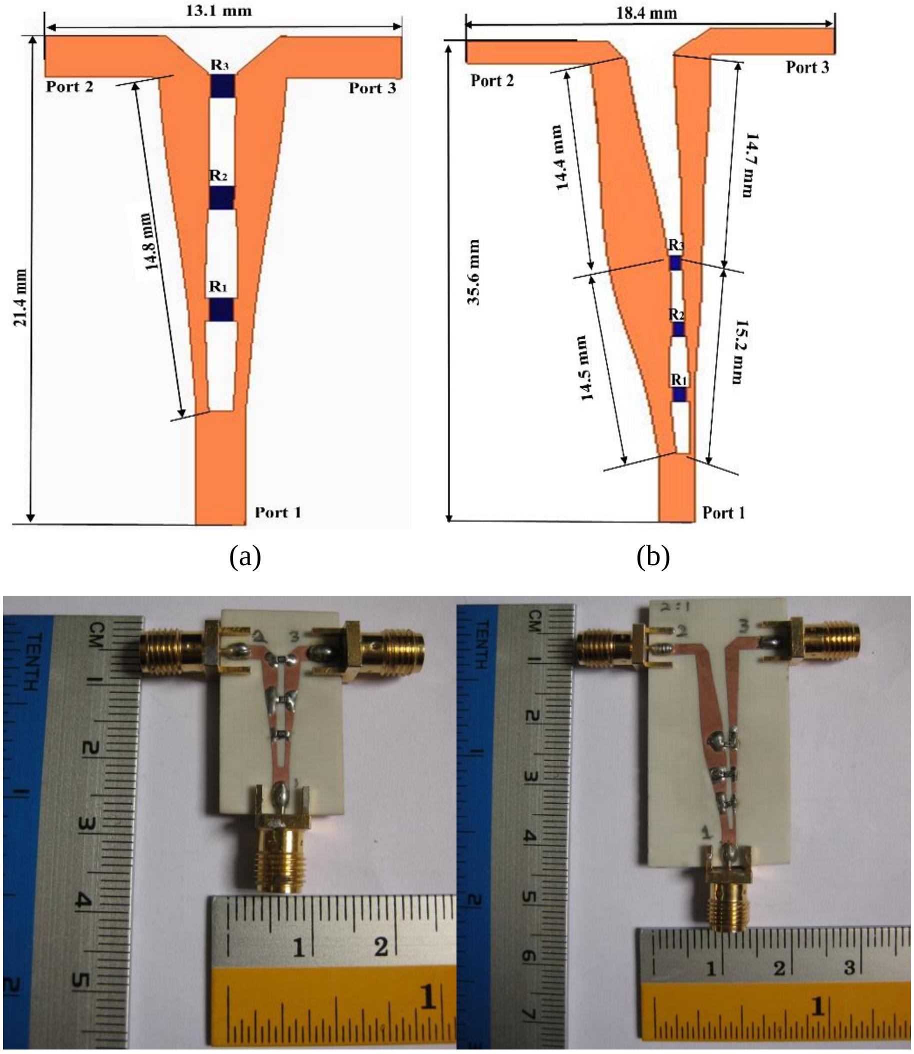
where,

$$[\text{ABCD}]_{Total}= [\text{ABCD}]_{\frac{R_3}{2}} \cdot [\text{ABCD}]_{1st\,section} \cdot [\text{ABCD}]_{\frac{R_2}{2}} \cdot [\text{ABCD}]_{2nd\,section} \cdot [\text{ABCD}]_{\frac{R_1}{2}} \cdot [\text{ABCD}]_{3rd\,section} \tag{5.a}$$

The same procedure is also applied to unequal-split UWB TTL WPD to find the required three resistors. Figure 3 shows the layouts and prototypes of the designed compact 2-way equal and 2:1 unequal split TTLs UWB WPDs.

Table 1. Calculated and optimized parameters for UWB equal and 2:1 unequal split WPD using tapered lines.

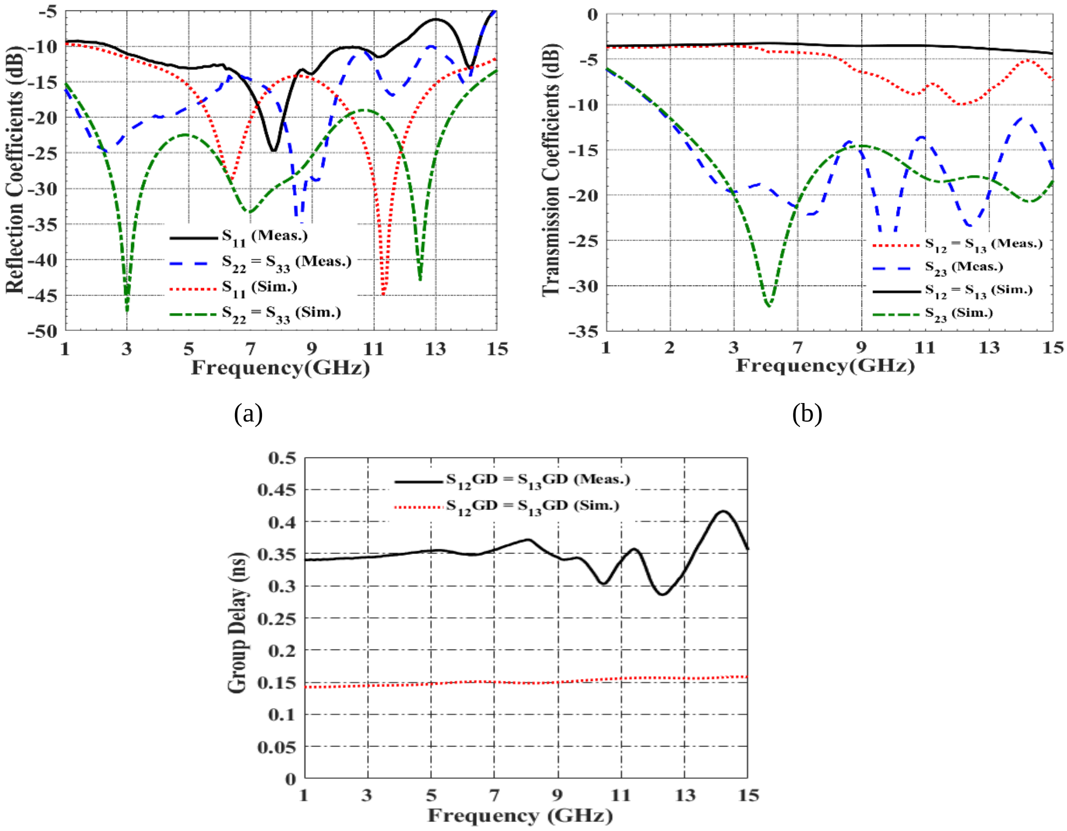
Parameters		Z_S (Ω)	Z_L (Ω)	**d (mm)**	**Resistors (Ω)**
Equal split		100	50	14.8	R_1=20, R_2= 120 and R_3=130
Unequal split	1st upper section	75	35.36	14.5	R_1=82 , R_2= 620 and R_3=470
	1st lower section	150	70.71	15.2	
	2nd upper section	35.36	50	14.4	
	2nd lower section	70.71	50	14.7	



(a) (b)

(c) (d)

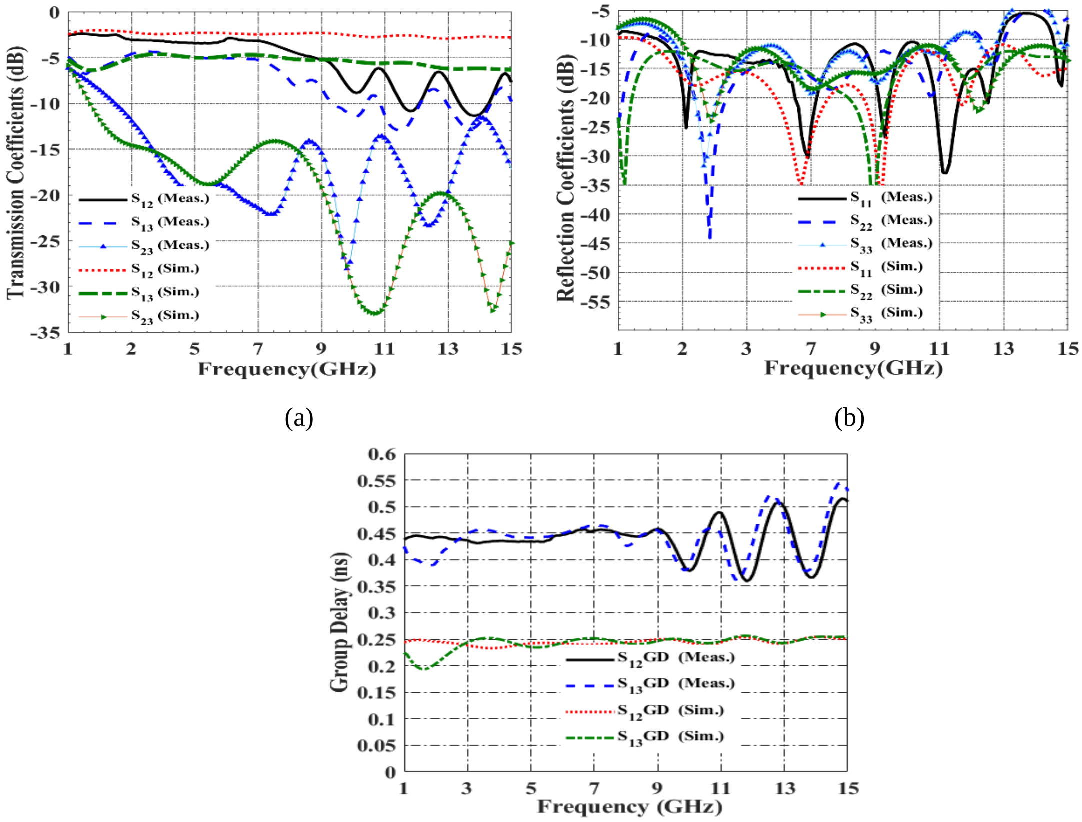
Figure 3. (a) and (b) Configuration and (c) and (d) fabricated prototypes of the proposed compact 2-way equal and 2:1 unequal split TTLs UWB WPDs, respectively.



(a) (b)

(c)

Figure 4. Measured and simulated (a) return loss (b) insertion loss and (c) group delay of the proposed 2-way equal split TTLs UWB WPD.



(a) (b)

(c)

Figure 5. Measured and simulated (a) return loss (b) insertion loss and (c) group delay of the proposed 2-way 2:1 unequal split TTLs UWB WPD.

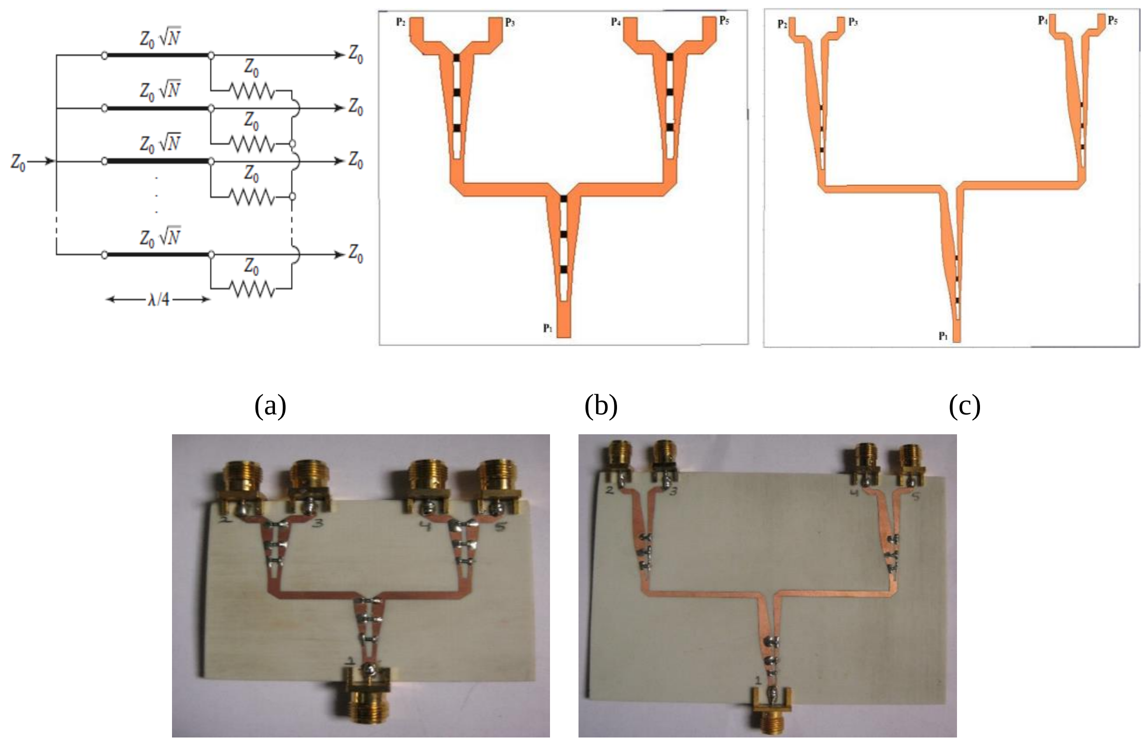
As it is clear from Figure 4a, the simulated and measured S_{11} is better than -10.7 and -10.1 through (1.6 GHz to more than 15 GHz) and (2.4 GHz -11.7 GHz), respectively. However, the simulated and measured $S_{22}= S_{33}$ is better than -18.7 and -10.4 through (less than 1 GHz to more than 15 GHz) and (less than 1 GHz -14.5 GHz), respectively. From Figure 4b, the simulated and measured transmission coefficients, $S_{12} =S_{13}$, are around -3 dB and -3 ± 0.8 dB, respectively with a disturbance in the measured one beyond 7.5 GHz because the impedance mismatch becomes worse at higher frequencies. In addition, for non-pure TEM transmission line at higher frequencies, the insertion loss increased due to the increase in conductor and dielectric losses [5]. Furthermore, a good isolation between the output ports is obtained (below -14 dB) for both simulated and measured results throughout the UWB frequency range. Figure 4c indicates constant group delays of approximately 0.15 ns (Sim.) and 0.35 ns (Meas.) and this difference is due to fabrication and measurement tolerance. However, for 2:1 unequal split WPD, as shown in Figure 5a, throughout the UWB frequency range, the simulated and measured S_{11}, S_{22} and S_{33} are below -10 dB. The simulated and measured S_{12} and S_{13} are around -2 dB and -5 dB and -2± 1.5 dB and -5± 0.9 dB, respectively with a degradation at high frequencies (beyond 7.5 GHz) for the measured results. Also, the simulated and measured isolation between output ports is better than -14 dB. Constant group delays of 0.26 ns (Sim.) and 0.45 ns (Meas.) are obtained, as indicated in Figure 5c. A comparison to the other UWB WPDs (equal and unequal split) in the literature is shown in Table 2.

3. COMPACT 4-WAY TTLS UWB WPD

The output ports of WPD can be extended to N ports, as shown in Figure 6a. However, there will be a crossover for the resistors, which is difficult to realize, especially in planar technology. N-way WPD can also be obtained by cascading connection (stepped multiple sections), which avoids the resistors' crossover and this method is used in this paper to design 4- and 8-way WPDs. Although a design equation can be used to control the split ratio of multiple sections [24]-[26], for simplicity in this work, the same designed 2-way equal and 2:1 unequal split TTLs UWB WPDs in section 2 are used to design 4-way UWB WPD. In 4-way equal split UWB WPD, one fourth of the input power will be delivered to each one of the four output ports. However, for 4-way 2:1 unequal split UWB WPD, 2/3 of the input power will be delivered unequally (2:1) to ports 2 and 3; i.e., port 2 will have 4/9 of the input power and port 3 will have 2/9; in addition, 1/3 of the input power will be delivered to ports 4 and 5; i.e., port 4 will have 2/9 of the input power and port 5 will have 1/9. The layouts and prototypes of the proposed dividers are shown in Figure 6. For 4-way equal split WPD, Figure 7a shows good matching at the input and output ports; i.e., the simulated and measured S_{11} is better than -10.4 and -10.8 through (3.55 GHz – 13.3 GHz) and (3.55 GHz -12.2 GHz), respectively. In addition, $S_{22} = S_{33} = S_{44} = S_{55}$ (< -21 dB (Sim.) and < -13 dB (Meas.) throughout the UWB frequency range. From Figure 7b, the simulated and measured transmission coefficients, $S_{12} = S_{13} = S_{14} = S_{15}$ are equal to -6.02 ± 1 dB and -6.02 ± 1.6 dB, respectively with a degradation beyond 7GHz (for S_{15}) and 7.5 GHz, because at high frequencies, conductor and dielectric losses are increased for non-pure TEM transmission line. Figure 7c shows a constant simulated group delay of approximately 0.38 ns and due to the fabrication and measurement tolerance, the measured one is around 0.55 ns for all transmission coefficients. As noticed, this group delay is greater than that of 2-way equal split WPD because of the long path that the signal takes from port 1 to the output ports (2 stages). Furthermore, in Figure 7d, the simulated and measured isolation between the output ports $S_{23} = S_{45}$ and S_{34} is better than -13.8 dB and -20 dB, -14.4 dB and -16.3 dB, respectively throughout the UWB frequency range. However, for 4-way 2:1 unequal split WPD, the simulated and measured S_{11} is better than -11.1 dB and -11.2 dB through (3 GHz to more than 16 GHz) and (2.4 GHz -12GHz), respectively and S_{22}, S_{33}, S_{44} and S_{55} are < -10 dB, as depicted in Figure 8a and Figure 8b. The simulated and measured transmission coefficients in Figure 8c, S_{12}, $S_{13} = S_{14}$ and S_{15} are around -4 dB, -7 dB and -10 dB and -4 dB ± 1, -7 ± 0.7 dB and -10 ± 1dB, respectively, with a degradation beyond 7.5 GHz. The group delay in Figure 8d is around 0.6 ns (Sim) and 0.8 ns (Meas.), which implies the long path that the signal takes due to the other sections required for matching in both stages. Good isolation between the output ports is obtained, as shown in Figure 9e, throughout the UWB frequency range, where the simulated and measured $S_{23} = S_{45}$ and S_{34} are better than -10.3 dB and -20 dB and -22 dB and -25 dB, respectively.

Table 2. Comparison to related works in the literature.

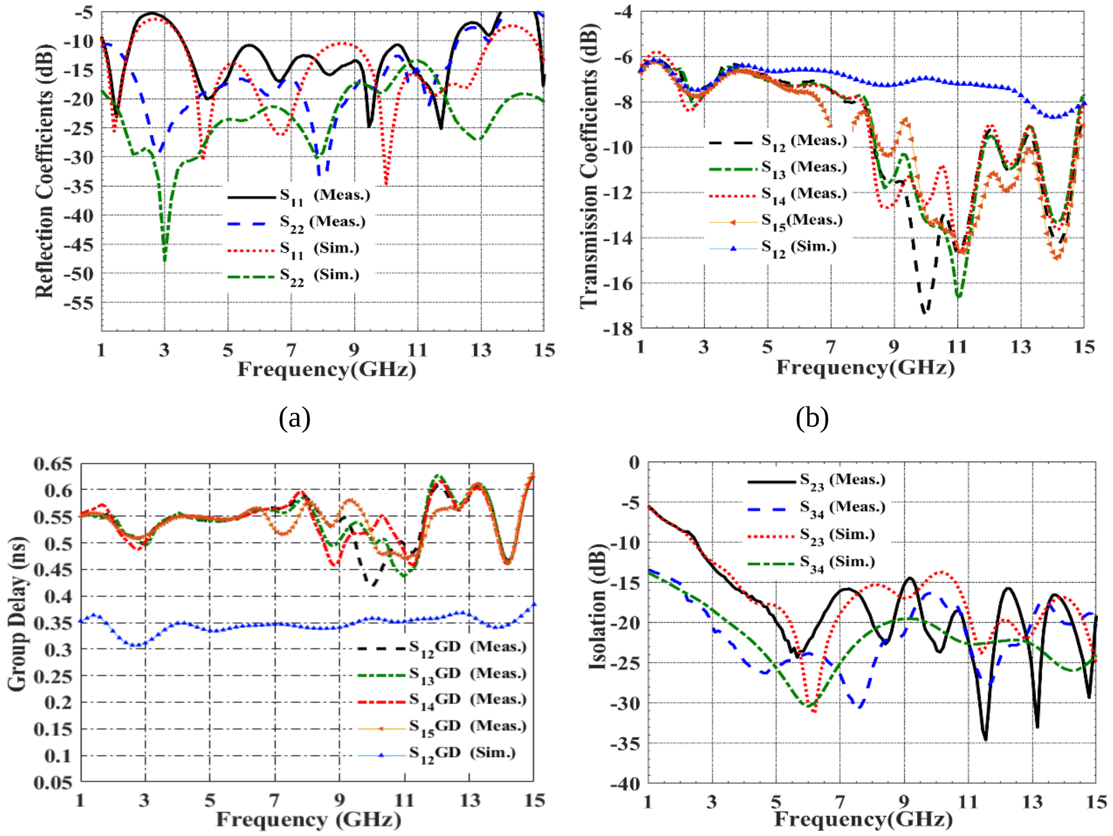
Ref.	**Substrate h(mm)/ ε_r**	**Technique used**	**Tr.(mm)**	**Rs**	**Fc (GHz)**	**BW (GHz)**	**Overall area (mm^2)**	**S_{11} (dB) <**	**S_{23} (dB) <**	**S_{12} (dB)**	**S_{13} (dB)**
EQUAL SPLIT											
This work	**0.813/ 3.55**	**1 section of TTLs**	**14.8**	**3**	**3.1**	**2.4-11.7**	**≈ 21.4x13.1**	**-10.1**	**-14**	**≈- 3±0.8**	**≈-3±0.8**
[9] 2-way Single layer	0.508/ 2.2	2 sections TTLs and UTLs	TTL =4 & UTL =3	1	6.85	3.1-10.6	≈15.51x15.47	-11	-15	≈-3±0.6	≈-3±0.6
[10], 2-way Single layer	0.508/ 2.2	4 CUTLTs based on micro-GA	1st=4.646, 2nd=4.131, 3rd=3.386 & 4th =3.696	4	6.85	3.1-10.6	≈20.85x9.5	-14	-17	≈-3±0.5	≈-3±0.5
[8], 2-way Single layer	0.8/ 3.58	2 sections UTL and TTL	UTL =3.2 & TTL =11	2	7	3.1-10	≈21.1x6.3	-11	-12	≈-3±1.8	≈-3±1.8
UNEQUAL SPLIT											
This work	**0.813/ 3.55**	**2 sections of TTLTs**	**1st =15.2** **2nd =14.7**	**3**	**3.1**	**2.3-12.9**	**≈35.6x18.4**	**-10.1**	**-14**	**≈-2±1.5**	**≈-5±0.9**
[12] 2-way 2:1, Single layer	0.1/ 2.33	2 sections of TTLTs	1st =27.5 2nd =27	5	2	2-12	76 x 28.5	-11.7	-15.5	≈-1.76±0.8	≈4.77±1
[13] 3-way 4:3:3, Single layer	0.635/ 2.33	2 sections of TTLTs	1st=27.5/28 2nd =27/28	4	2	2-12	≈59.18x 40	-10	S_{23} <-15 S_{24} & S_{34} <-10	≈-4	S_{13}=S_{14}≈-5.5
[14] 2-way 3:1, Single layer	0.508/ 2.33	ACTLs & TTLs	1st =15.9 2nd =35	2	NA	3.1-10.6	81.3. x 14	-12.3	-17	≈−1.42	≈−5.8



(a) (b) (c)

(d) (e)

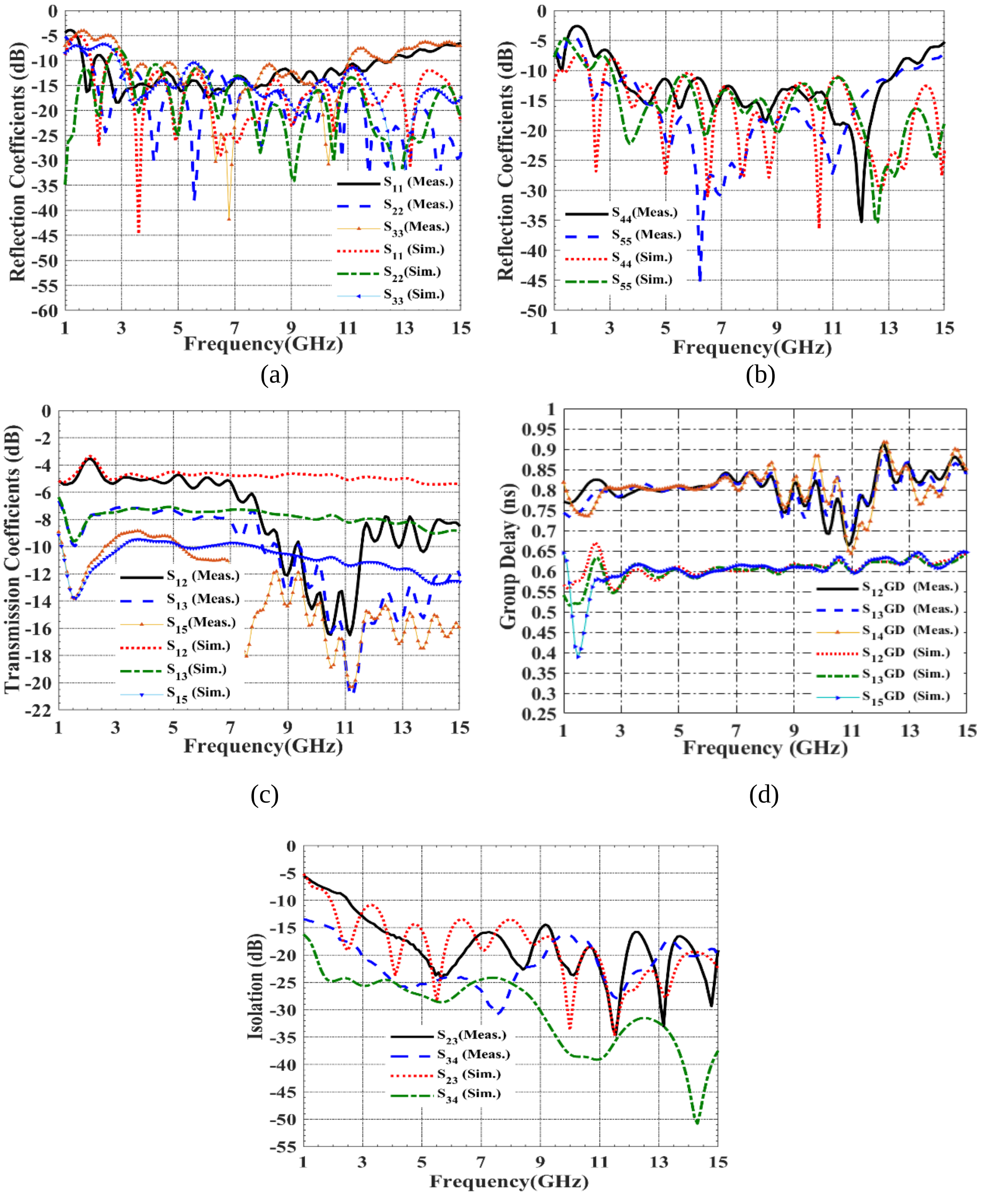
Figure 6. (a) N-way equal split WPD [5], (b),(c) Configuration and (d) fabricated prototypes of the proposed compact 4-way 2:1 equal and unequal split TTLs UWB WPDs, respectively.



(a) (b)

(c) (d)

Figure 7. Measured and simulated (a) return loss (b) insertion loss (c) group delay and (d) isolation of the proposed 4-way TTLs UWB equal split WPD.



(a) (b)

(c) (d)

(e)

Figure 8. Measured and simulated (a), (b) return loss (c) insertion loss (d) group delay and (e) isolation of the proposed 4-way 2:1 unequal split TTLs UWB WPD.

4. COMPACT 8-WAY TTLS UWB EQUAL SPLIT WPD

An 8-way UWB equal split WPD is obtained by using three stepped sections with the help of the pervious designed 2-way equal split WPD. The first 2-way WPD is carrying two 2-way WPDs and each one is carrying two 2-way WPDs; at the end an 8-way WPD is obtained, as depicted in Figure 9. Each port will have 1/8 of the input power.

In Figure 10a, all output ports are matched in UWB frequency band and S_{11} is better than -10.2 dB through (3.9 GHz -13.4 GHz). The simulated transmission coefficients $S_{12} = S_{13} = S_{14} = S_{15} = S_{16} = S_{17} = S_{18} = S_{19}$ are equal to -9.03 ± 1.5 dB throughout the UWB frequency range. In Figure 10c, the group delay is around 0.6 ns for all the signal paths. Furthermore, the simulated isolation $S_{23} = S_{45} = S_{67} = S_{89}$ and $S_{34} = S_{56} = S_{78}$ is below -18.2 dB and -26 dB throughout the UWB band, as shown in Figure 10d.

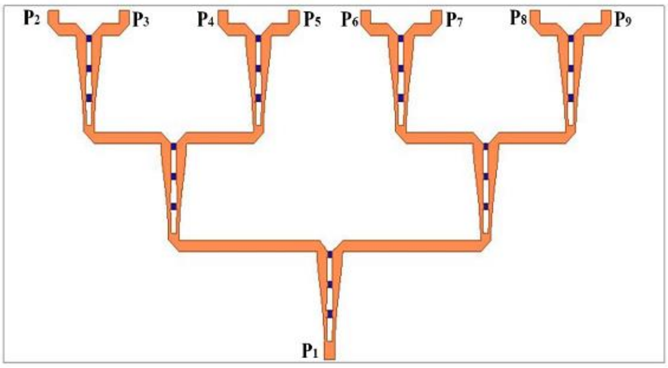
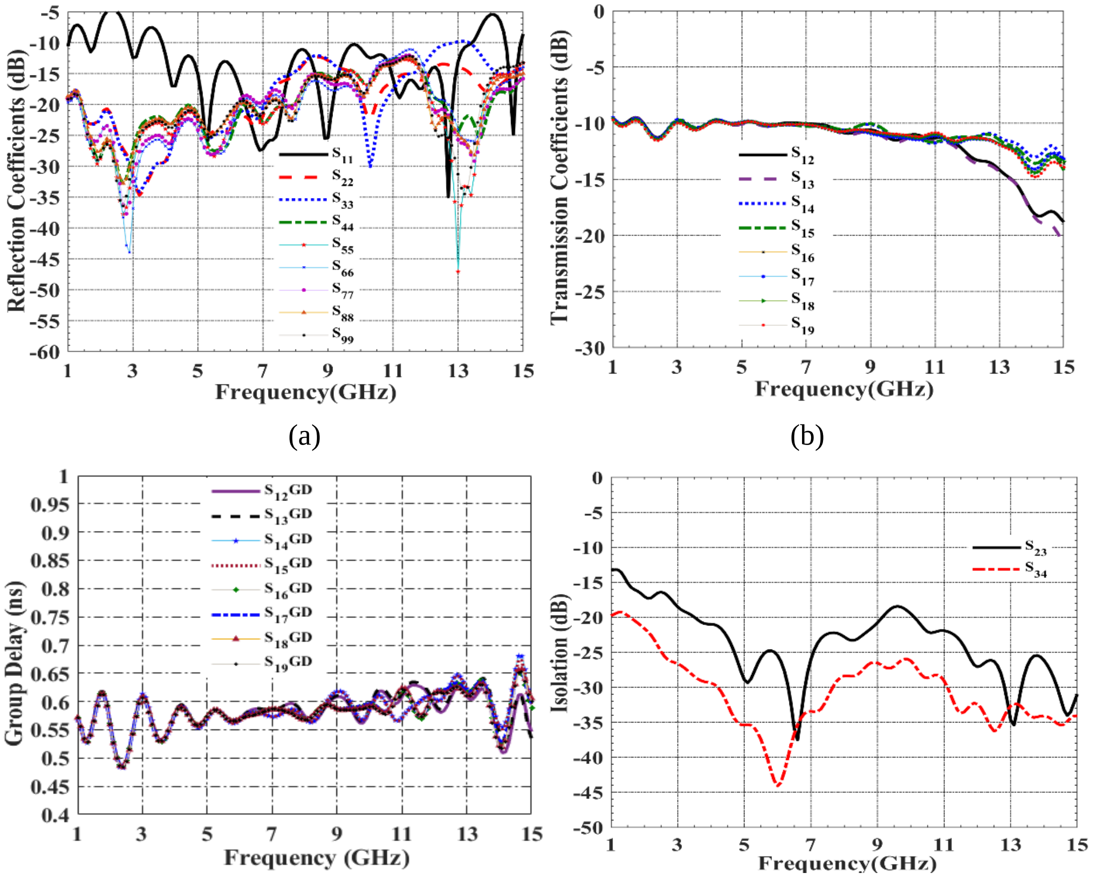


Figure 9: Layout of the proposed compact TTL UWB 8-way equal split WPD.



(a) (b)

(c) (d)

Figure 10. Simulated (a) return loss (b) insertion loss (c) group delay and (d) isolation of the proposed 8-way TTLs UWB equal split WPD.

5. CONCLUSIONS

Exponentially λ/4 Tapered Transmission Line Transformers (TTLTs) are used in this paper to design a compact N-way Ultra Wide Band (UWB) equal and unequal split Wilkinson Power Divider (WPD) with a cascaded topology. As a building block for N-way divider, 2-way equal and 2:1 unequal split TTLs UWB WPDs are designed, simulated and fabricated. Both dividers show good input and output matching, isolation and constant group delay. 2-stage 4-way equal split and 2:1 unequal split TTLs UWB WPDs are designed based on the designed 2-way dividers with good simulation and measured results in terms of reflection, transmission coefficients, isolation and group delay. Finally, based on 2-way equal split WPD, a 3-stage 8-way equal split WPD is designed with good simulation results. The proposed N-way WPD can be used as a feeding network for an antenna array. For future work, one can apply such different networks to linear UWB antenna arrays.

ACKNOWLEDGEMENTS

This work was supported by the University of Science Malaysia through the RUI Grants (1001/PELECT/801405) and (304/PELECT/6315294).

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ملخص البحث:

في هذه الورقة، يتم تصميم مقسِّمات قدرة من طراز ويلكنسون، مدمجة ومتعددة الطرق في نطاق الترددات فائق العرض، لاستخدامها في خطوط النقل المتدرِّجة المنفصلة بشكلٍ متساوٍ وغير متساوٍ والمبنية على أساس ربع طول الموجة. بدايةً، تم تصميم مقسِّمات قدرة ويلكنسون بطريقتين، ثم محاكاتها وسَلْسَلتها؛ للحصول على مقسِّمات قدرة ويلكنسون في نطاق الترددات فائق العرض ذات 4 طرق (بشكلٍ متساوٍ وغير متساوٍ) وذات 8 طرق (مقسمة بشكل متساوٍ). كذلك تم تصنيع مقسِّمات قدرة ويلكنسون ذات طريقين وذات 4 طرق (مقسَّمة بشكل متساوٍ وغير متساوٍ) وفحصها. وتبين أن نتائج القياس ونتائج المحاكاة لجميع المقسِّمات الّتي تم تصميمها كانت جيدة من حيث: الإدخال، وفقْد الرجوع، وتأخير المجموعة على مدى نطاق الترددات فائق العرض.

أُجري تحليل تلك المقسِّمات باستخدام حزمة برمجيات المحاكاة البنيوية للترددات العالية التابعة لبرمجيات (ANSYS) والمسماة (HFSS) التي ترتكز على طريقة العناصر المتناهية (FEM). من جهة أخرى، تم استخدام إحدى دوالّ (MATLAB) لإيجاد القيم المثالية للمقاومات الثلاث المختارة لتحقيق العزل التام. وللتحقق من النتائج، تمت مقارنة نتائج المحاكاة مع النتائج المقاسة.