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A Design Procedure for Multi-Section Micro-Strip Wilkinson Power Divider with Arbitrary Dividing Ratio

Puria Salimi

***Abstract*—In this article a designing procedure based on Chebyshev impedance matching is introduced to design coupled line Wilkinson power divider. The main objective in this paper is to introduce the simple procedure for Wilkinson power divider designing that can be used for both coupled and separated transmission lines. The Wilkinson power divider is mentioned as a four port network and even-odd mode analysis is used to calculate the characteristic impedances and resistor values. To clarify the advantages of this approach several designing for arbitrary dividing ratio with several coupling factor are done and the frequency response of some of them are compared together. The results show the simplicity of the introduced approach and also show the usability of this to use for coupled and decoupled Wilkinson power dividers.**

***Index Terms*—circuit design, impedance matching, Wilkinson power divider, transmission line, Chebyshev polynomial**

I. INTRODUCTION

THE Wilkinson power dividers are widely use in microwave circuits. There are some unique properties such as simple structure, isolation between output ports and good matching in all ports that make them useful in communication systems. The Wilkinson power divider invented in 1960[1]. In primary dividers the bandwidth was narrow and the best performance of the divider was at the center frequency. In order to increase the bandwidth, series connection of sections were used in 1968 [2] that had great impact on bandwidth and caused it became wider. At first these device was built such a way that divides the input power to output ports equally. In 1965 the power divider was built for unequal purpose [3] and the even-odd mode analysis was used for designing. Then in 1971 this method used forn-section dividers [4]. Despite of the simplicity of structure, the designing is complex. Till now variety of designing methods are introduced for different bandwidth[5-13] and variety dividing ratio [14-17] and the drivers are fabricated on different type of transmission lines and structures [14-21] such as coupled and separated [22-24]. In this paper the method will be introduced that in addition to the simplicity, it can be used for coupled and separated transmission lines.

At first the three-port Wilkinson power divider is considered as a four-port network. Then it divided to two independent circuit called even and odd mode networks. The even mode network is similar to matching transformer.

Puria Salimi, Azad university of Najaf-Abad, Iran

To calculate the line's characteristic impedances of it, the Chebyshev polynomial and procedure is used. According to these results and the initial assumption, the odd mode characteristic impedances will be calculated. In section II the Chebyshev polynomial is introduced and explained how to use it. In section III an error function is calculated. By minimizing this function the amount of resistors will be obtained. Several power dividers with variety of dividing ratio are design and simulated in section IV and the output results are shown. In order to show the practical result, an unequal Wilkinson power divider is fabricated in section V.

II. ANALYSIS

Fig.1 shows a four port network is mentioned in section I. As it is pointed in introduction, the four port network, divided in to even-odd mode networks [4]. In even mode E_a=E_b, and here is zero current in the section resistors. It is only if the voltage distributions on the two sides are identical. With this assumption the four port network resulting in two decoupled networks shown in Fig.2 (a) & (b). According to dividing ratio (k), and identical distribution of voltage in two sides of the network, the $\{Z_{ea_i}\}$ and $\{Z_{eb_i}\}$, $i = 1, \ldots, n$should satisfy the following;

$$Z_{eb_i} = k_e Z_{ea_i}\ ,\ i = 1, \ldots, n \tag{1}$$

$$\frac{R_{44}}{R_{11}} = \frac{R_{33}}{R_{22}} = k_e \tag{2}$$

In this case the $\{Z_{ea_i}\}$ can be calculated by using Chebyshev multi-section matching transformer design and Chebyshev polynomial[24] and according to $\{Z_{ea_i}\}$, the $\{Z_{eb_i}\}$ can be calculated. In odd network, E_a= $-E_b$. In this situation networks shown in Fig.2 (c) & (d) are derived from Fig.1. The odd impedances are following the relations below;

$$Z_{ob_i} = k_o Z_{oa_i} \tag{3}$$

$$\frac{R_{44}}{R_{11}} = \frac{R_{33}}{R_{22}} = k_0 \tag{4}$$

In order to have equal dividing ratio both in even and odd mode networks k_e and k_o should be equal ($k_e = k_o = k$). In Fig.3 (a), a three port Wilkinson power divider, derived from Fig.1 is shown. In order to have the desired three port network which is driven from the network shown in fig.1, R_{11} and R_{44} should be parallel. In this situation fig.3 (a) is obtained. The even-odd mode of this structure is shown in fig.3 (b) & (c). As it is seen there is no deference between even mode of three and four networks and the only deference, is in odd mode. Thus we can calculate the even mode impedances and as a result, the odd mode impedances of this three network by using the Chebyshev equations described in section III.In even mode Fig.1 and Fig.3 (a) are identical if;

$$R_0 = R_{11} \parallel R_{44} \quad (5)$$

and Fig.3 satisfy (1),(2). In odd mode, Fig.1 and Fig.3 (a) are identical if;

$$R_{11} = R_{44} = 0 \quad (6)$$

and(3),(4)are satisfied. The (a) side even and odd mode three port Wilkinson power divider are shown in Fig.3 (b) & (c). The (b) side even and odd mode of Fig.3 (a) is similar to (a) side.

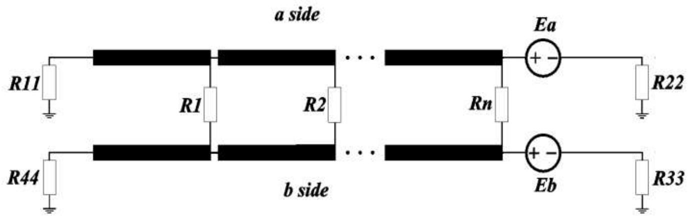
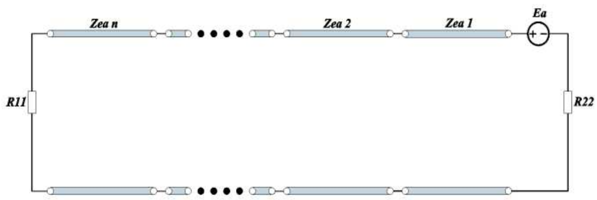
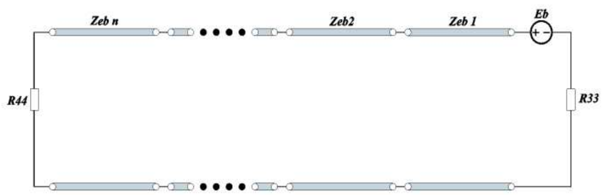


Fig.1. Four port coupled transmission lines in n section cascade.



(a)



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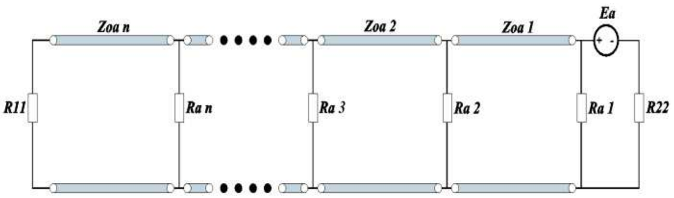

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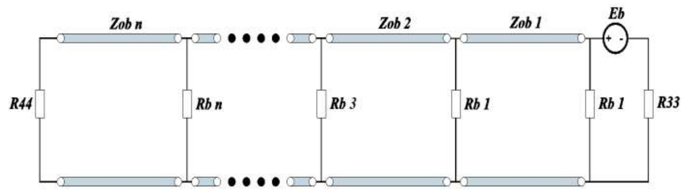
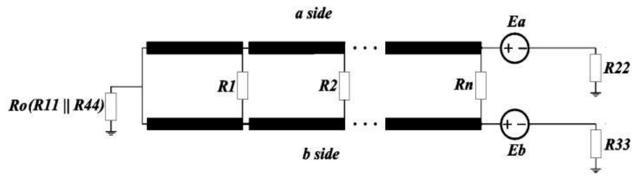
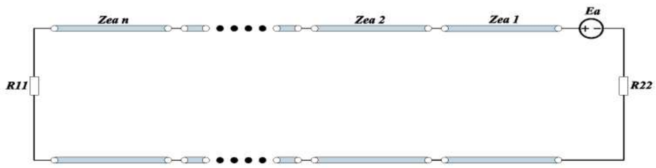


(d)

Fig.2. Even and odd mode networks of Fig.1. (a), (b): even-mode networks, (c),(d): odd-mode networks



(a)



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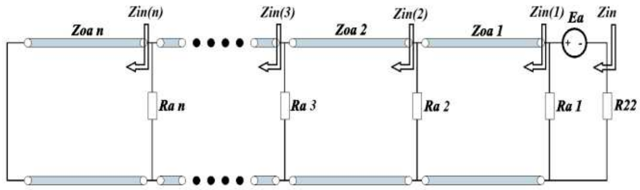


(c)

Fig. 3. The three port Wilkinson power divider, derived from Fig.1 (a): three port Wilkinson power divider, (b) even mod of a side, (c) odd mod of a side.

III.CHEBYSHEVPOLYNOMIYAL

The Chebyshev polynomial is denoted by $T_n(x)$ where n is the degree of polynomial. The first three Chebyshev polynomials are [24]

$$T_1(x) = x \quad (7)$$

$$T_2(x) = 2x^2 - 1 \quad (8)$$

$$T_3(x) = 4x^3 - 3 \quad (9)$$

And higher order polynomials can be found by using following formula;

$$T_n(x) = 2xT_{n-1}(x) - T_{n-2}(x) \quad (10)$$

Now we can synthesize a Chebyshev equal passband by making $\Gamma(\theta)$ proportional to $T_n(x)$, where $x = sec\theta_m cos\theta$.

$$\Gamma(\theta) = 2e^{-jN\theta}[\Gamma_0 cosN\theta + \Gamma_1 \cos(N-2)\_ + \cdots + \Gamma_n \cos(N-2n)\,\theta + \cdots] = Ae^{-jN\theta}\_ \; T_N(sec\theta_m cos\theta) \quad (11)$$

Where N indicates number of sections and the last term in the series of (11) is $(\frac{1}{2})\Gamma_{N/2}$ for N even and $\Gamma_{(N-1)/2}cos\theta$ for N odd and $\theta_m < \theta < \pi - \theta_m$.

According to $\Gamma(\theta)$, the Γ_n , $n = 1, \dots, N$ can be found and as a result the $\{Z_{ea_i}\}$, by using followings;

$$\Gamma_n = \frac{Z_{n+1} - Z_n}{Z_{n+1} + Z_n} \qquad (12)$$

$$\Gamma_n \approx \frac{1}{2} Ln \frac{Z_{n+1}}{Z_n} \qquad (13)$$

According to Fig.2 (a), Table.1 shows several impedance matching between R_{11} and R_{22} that are calculated with Chebyshev procedure, Γ_m is maximum allowable reflection coefficient magnitude in the passband, then from (11), $\Gamma_m = |A|$. Here the Γ_m=0.05.

The degree of coupling is defined by the coefficients c_i , where

$$c_i = \frac{Z_{ea_i} - Z_{oa_i}}{Z_{ea_i} + Z_{oa_i}} \qquad (14)$$

The biggest coefficient is for the first section and the smallest one is for the last section. As is clear when the even mode section impedances are clarified and the coefficients are chosen, the odd mode section impedances are reachable.

TABLE.1Several impedance matching transformers between R_{11} and R_{22}

n	R_{11}	R_{22}	Γ_m	Γ_0	Γ_1	Γ_2	Γ_3	Zea_3	Zea_2	Zea_1
1	50	100	0.05	0.17	0.17	----	----	----	----	1414.4214
1	70	31.6228	0.05	0.2	0.2	----	----	----	----	47.0489
1	175	79.0569	0.05	0.2	0.2	----	----	----	----	117.6221
2	50	100	0.05	0.1	0.15	0.1	----	----	164.0269	121.9312
2	70	31.6228	0.05	0.11	0.17	0.11	----	----	55.9714	39.5487
2	175	79.0569	0.05	0.11	0.17	0.11	----	----	139.9285	98.8717
3	50	100	0.05	0.07	0.1	0.1	0.07	114.9613	141.4214	173.9715
3	70	31.6228	0.05	0.08	0.12	0.12	0.08	60.0167	47.0489	36.8830
3	175	79.0569	0.05	0.08	0.12	0.12	0.08	150.0416	117.6221	92.2075

IV.ERROR FUNCTION

In this paper regarded to input impedances from output ports, the error function is written and by minimizing, the amount of section resistors obtained. In order to calculate the value of section resistors (Ra_1,Ra_2, ... ,Ra_n) we use the odd mode network in fig.3 (c). This means that, according to characteristic impedances of the lines, the equivalent impedance from output port is obtained. (The characteristic impedances are calculated from section *III* and R_{11}=*50* ohm.) Then we matched this equation to port's resistor R_{22}. Thus an equation consist of isolated resistors, is calculated. By minimizing this equation the value of resistors are obtained. We can use the same approach for another odd network to calculate the value of Rb_1,Rb_2, ... ,Rb_n.

According to Fig.3 (c), the impedance witch is seen from output port is written as follows

$$Z_{in} = Z_{in}(1) \| Ra_1 \qquad (15)$$

$$Z_{in}(1) = Z_{oa1} \frac{Z_{oa1} + j(Z_{in}(2) \| Ra_2)\tan(\theta)}{(Z_{in}(2) \| Ra_2) + jZ_{oa1}\tan(\theta)} \qquad (16)$$

$$Z_{in}(2) = Z_{oa2} \frac{Z_{oa2} + j(Z_{in}(3) \| Ra_3)\tan(\theta)}{(Z_{in}(3) \| Ra_3) + jZ_{oa2}\tan(\theta)} \qquad (17)$$

$$Z_{in}(n-1) = Z_{oa(n-1)} \frac{Z_{oa(n-1)} + j(Z_{in}(n) \| Ra_n)\tan(\theta)}{(Z_{in}(n) \| Ra_n) + jZ_{oa(n-1)}\tan(\theta)} \qquad (18)$$

And for the last step $Z_{in}(n)$ is

$$Z_{in}(n) = \frac{Z_{oan}}{j\tan(\theta)} \qquad (19)$$

Then the Z_{in} should be equal to R_{22}. Now we have an equation consist of odd mode characteristic impedances, R_{11}, R_{22} and the section resistors. Except the section resistors all elements are known.

For a two section (n=2) power divider the error function is as follows

$$Z_{in}(2) = \frac{Z_{oa2}}{j\tan(\theta)} \qquad (20)$$

$$Z_{in}(1) = Z_{oa1} \frac{Z_{oa1} + j\left(\frac{Z_{oa2}}{j\tan(\theta)} \| Ra_2\right)\tan(\theta)}{\left(\frac{Z_{oa2}}{j\tan(\theta)} \| Ra_2\right) + jZ_{oa1}\tan(\theta)} \qquad (21)$$

$$Z_{in} = Z_{oa1} \frac{Z_{oa1} + j\left(\frac{Z_{oa2}}{j\tan(\theta)} \| Ra_2\right)\tan(\theta)}{\left(\frac{Z_{oa2}}{j\tan(\theta)} \| Ra_2\right) + jZ_{oa1}\tan(\theta)} \| Ra_1 \qquad (21)$$

The *Error Function* is as follows

$$\left(Z_{oa1}\frac{Z_{oa1}+j\left(\frac{Z_{oa2}}{j\tan(\theta)}\|Ra_2\right)\tan(\theta)}{\left(\frac{Z_{oa2}}{j\tan(\theta)}\|Ra_2\right)+jZ_{oa1}\tan(\theta)}\|Ra_1\right)-\ R_{22}=0 \qquad (22)$$

V. NUMERICAL CALCULATION

In this section some examples are calculated for deferent dividing ratio and deferent number of sections and their parameters are tabulated in related tables. Where *c* is the coupling factor, *n* is number of sections and *k* is dividing ratio. In each examples R_{11} and R_{44} are selected in such a way that $R_{11}||R_{22} = 50\ ohm$, and g>30, means that transmission lines are separated. The frequency response of some of these examples are simulated and compared.

Sample1:

Based on described procedure, a one section (*n=1*) power divider in f_0 =1.5GHz with deferent dividing ratio is mentioned and its structure is shown in Fig.4. Theparameters for variety of *k* are listed in Table.2 where R_0=50 ohm. The frequency response of case 6 and case 10 are shown in Fig6.

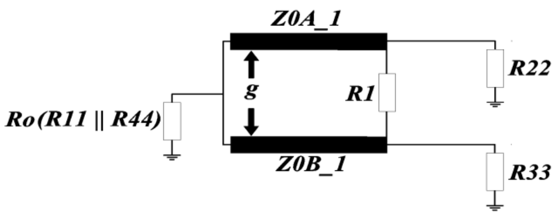


Fig.4.The one section Wilkinson power divider

Sample2:

Based on described procedure, a two section (*n=2*) power divider in f_0 =1.5GHz with deferent dividing ratio is mentioned and its structure is shown in Fig.5. Theparameters for variety of *k* are listed in Table.3 where R_0=50 ohm. The frequency response of case 6 and case 10 are shown in Fig7.

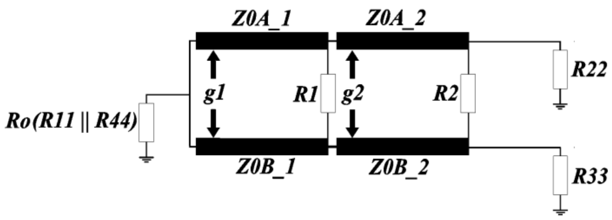
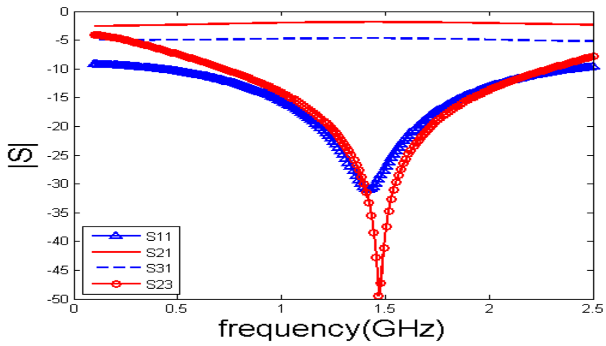
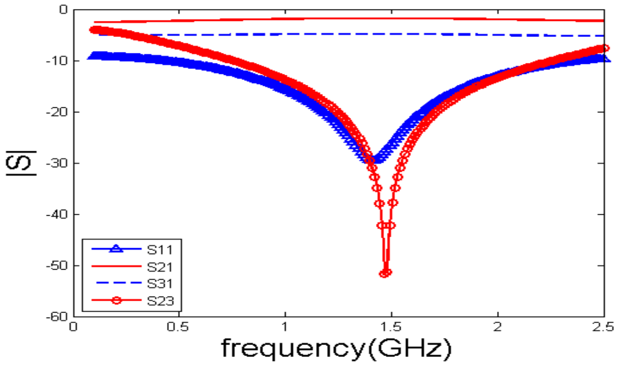


Fig. 5.The two section Wilkinson power divider

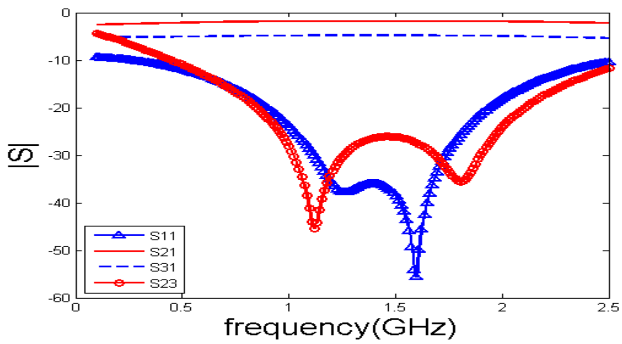


(a)

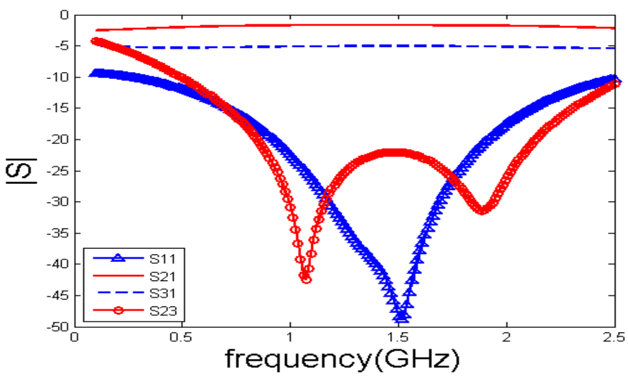


(b)

Fig. 6. The frequency response for example1 (a): case6, (b): case10



(a)



(b)

Fig. 7. The frequency response for example2 (a): case6, (b): case10

Comparing Fig.6 (a) with Fig.6 (b) and Fig.7 (a) with Fig.7 (b), it is seen that the frequency response of designs respectively are similar. The only deference of these designs is just characteristic impedances of transmission lines in deferent coupling factor when dividing ratio is constant. As a result the deference is in physical dimensions. This is more visible in higher dividing ratio.

As the elements in tables illustrate, the higher dividing ratio, the higher characteristic impedances and in the same dividing ratio, the higher coupling factor, the lower characteristic impedances. It means that when the coupling factor becomes higher, the width of the lines become wider. The coupling factor becomes higher from output ports to input port.

TABLE.2
The calculated parameters for one section Wilkinson power divider with variable dividing ratio (*k*)

case	n	k	Z0A_1	Z0B_1	R_1	R_{11}	R_{22}	R_{33}	R_{44}	c	g(mm)
1	1	1:1	70.7107	70.7107	100	100	50	50	100	0	>30
2	1	1:1.7	55.1843	93.8132	103	79.4118	38.34	65.1920	135	0	>30
3	1	1:2	51.4942	102.9884	106	75	35.3553	70.7107	150	0	>30
4	1	1:2.5	47.0489	117.6221	110	70	31.6228	79.0569	175	0	>30
5	1	1:1	63.9602	63.9602	100	100	50	50	100	0.1	2.33
6	1	1:1.7	49.9160	84.8573	103	79.4118	38.34	65.1920	135	0.1	2.22
7	1	1:2	46.3553	93.1565	106	75	35.3553	70.7107	150	0.1	2.42
8	1	1:2.5	42.5573	106.3932	110	70	31.6228	79.0569	175	0.1	2.45
9	1	1:1	59.8639	59.8639	100	100	50	50	100	0.165	1.87
10	1	1:1.7	46.7192	79.4227	103	79.4118	38.34	65.1920	135	0.165	1.67
11	1	1:2	43.5952	87.1903	106	75	35.3553	70.7107	150	0.165	1.75
12	1	1:2.5	39.8317	99.5794	110	70	31.6228	79.0569	175	0.165	1.45

Table.3
The calculated parameters for two-section Wilkinson power divider with variable dividing ratio (*k*)

Case	n	k	Z0A_1	Z0A_2	Z0B_1	Z0B_2	R_1	R_2	R_{11}	R_{22}	R_{33}	R_{44}	c_1	c_2	g1(mm)	g2(mm)
1	2	1:1	82.0135	60.9656	82.0135	60.9656	87	288	100	50	50	100	0	0	>30	>30
2	2	1:1.7	64.5643	47.1669	109.7594	80.1838	92	295	79.4118	38.34	65.1920	135	0	0	>30	>30
3	2	1:2	60.6111	43.7486	121.2222	87.4972	95	300	75	35.3553	70.7107	150	0	0	>30	>30
4	2	1:2.5	55.9714	39.5487	139.9285	98.8717	100	310	70	31.6228	79.0569	175	0	0	>30	>30
5	2	1:1	69.7904	55.1455	69.7904	55.1455	87	288	100	50	50	100	0.1	0.16	1.72	2.40
6	2	1:1.7	54.9419	42.6641	93.4012	72.5290	92	295	79.4118	38.34	65.1920	135	0.1	0.16	1.67	2.42
7	2	1:2	51.5778	39.5721	103.1556	79.1442	95	300	75	35.3553	70.7107	150	0.1	0.16	1.5	2.30
8	2	1:2.5	47.6296	35.7731	119.0740	89.4328	100	310	70	31.6228	79.0569	175	0.1	0.16	1.67	2.42
9	2	1:1	62.3133	51.6137	62.3133	51.6137	87	288	100	50	50	100	0.165	0.268	0.91	1.47
10	2	1:1.7	49.0556	39.9317	83.3945	67.8839	92	295	79.4118	38.34	65.1920	135	0.165	0.268	0.62	1.46
11	2	1:2	46.0520	37.0377	92.1039	74.0754	95	300	75	35.3553	70.7107	150	0.165	0.268	0.50	0.84
12	2	1:2.5	42.5267	33.4821	106.3168	83.7051	100	310	70	31.6228	79.0569	175	0.165	0.268	0.64	1.40

VI. PRACTICAL DIVIDER AND RESULTS

In order to clarify the effectiveness of this designing approach for practical use in this section, an unequal three-section coupled line Wilkinson power divider with k=1:2.5 and bandwidth 96% is fabricated with microstrip lines on FR4 substrate with a thickness 1.57 and dielectric constant 4.47. The coupling coefficients are c_3 = 0.377, c_2 = 0.268 and c_1 = 0.165. The value of characteristic impedances and section resistors are tabulated in Table.4 and the frequency response of this divider is shown in fig.9.

The physical design procedure is fully described in [20].Fig.8 shows the physical structure of the mentioned power divider witch is matched with R_L=50 ohm and the frequency response is shown in fig.9.

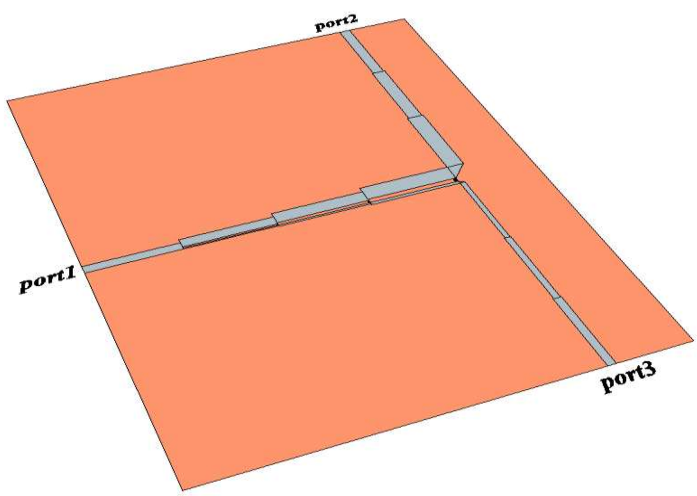
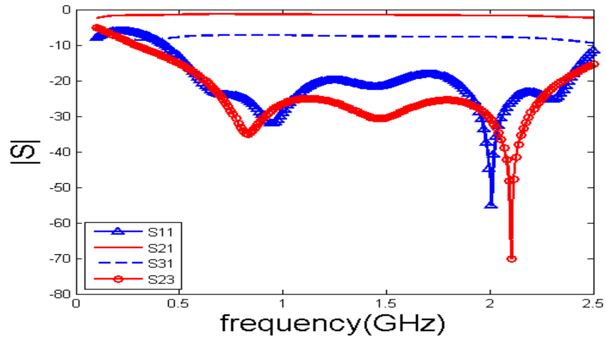


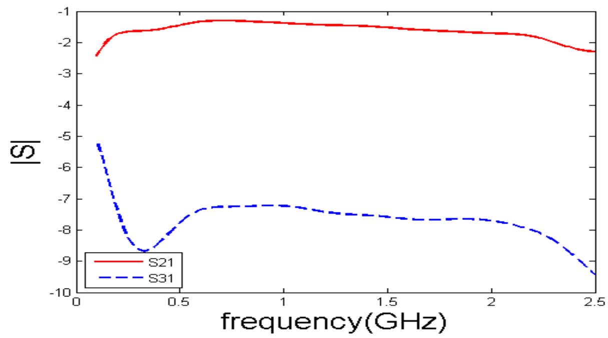
Fig. 8.The physical structure of the fabricated three-section coupled line Wilkinson power divider

Table.4
The calculated parameters for three-section Wilkinson power divider with *k=2.5*

	Section 1(n=1)	Section 2(n=2)	Section 3(n=2)
ZA	40.3691	35.7474	31.2253
ZB	100.9227	89.3686	78.0632
R_n	73	193	1361



(a)



(b)

Fig. 9. The frequency response for fig.7 (a): frequency response (b): power division to output ports

VII. CONCLUSION

A designing approach base on Chebyshev impedance matching for multi-section Wilkinson power dividers with coupled transmission lines with arbitrary dividing ratio is introduced. The method also can be used for separated Wilkinson power dividers designings. The Wilkinson power divider is mentioned as a four port network then it is divided to two separated networks named even and odd mode. In order to calculate the characteristic impedances the even mode and Chebyshev impedance matching method, and for calculating the section resistor values, the odd mode are used. By the introduced approach, several designs were done and the results are tabulated and the frequency response for some of them are compared. The results suggest the simplicity of the procedure and also usability for both coupled and separated Wilkinson power divider designings. The tables show that increasing the value of coupling factors leds to decreasing the characteristic impedances when the dividing ratio is constant. It means that reaching to higher dividing ratio more easily compared to separated transmission lines.

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Puria Salimi was born in Iran, in 1984. He received the Undergraduate degree from shiraz University, Iran, in 2006, B.Sc. degree from Chamran university of Kerman, Iran, in 2008, the M.Sc. degree from Azad university of Najaf-Abad, Iran, in 2013. His research interests are in various areas of electrical engineering such as high-frequency circuit design, metamaterial, antenna, communication circuits, and AVR projects.