Dual-Band 4-Way Wilkinson Power Divider Based on Improved Simplified Composite Right and Left Handed Transmission Lines

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Abstract **─** In this paper, by using improved simplified composite right and left handed transmission lines (I-S-CRLH-TL), a novel 4-way parallel Wilkinson power divider (WPD) is presented. The proposed WPD exhibits the benefits of excellent isolation and equal power split between output ports in the dual frequency band. Also, the dual-band nature of this divider, low cost and easy integration with printed circuits and printed antennas in a compact size makes this device a very good candidate for feeding dual-band antennas and microwave devices. The proposed divider is designed and fabricated on a low cost substrate with permittivity of 4.4 and thickness of 0.79 mm to work at two arbitrary frequency bands of 0.95 GHz and 2.43 GHz. There is a good agreement between simulated and measured results in all cases. The design concept of this paper can be easily extended to another type of dual-band microwave components.

Index Terms **─** Dual-band, metamaterial, Wilkinson power divider.

I. INTRODUCTION

Wilkinson power dividers (WPDs) are important and indispensable part of microwave circuits including filters, phase shifters and antenna arrays [1]-[4]. It is known that, traditional WPDs are implemented with quarter wave transmission lines (TLs). But it is clear that these WPDs exhibit degrees of limitation such as relatively narrow band and cannot satisfy the flexible multiband applications. Nowadays, due to the requirement of dual-band microwave or wireless communication systems, various techniques have been used to design multiband components which can provide a device to simultaneously use different frequency band [1]-[10]. One of these components is Wilkinson power divider (WPD). Recently, many efforts have been used to design dual-band and multiband WPDs [1], [4]-[8]. On the other hand, in the last decades, while a lot of works have been reported about designing of dual-band and multiband WPDs with two output ports, not much work have been reported on dual-band WPDs with more output ports. The 4-way dividers in [11,12] are based on conventional transmission lines and work only around a single frequency band. In [13], a 4-way divider was presented based on negative reflective index transmission lines (NRI-TL structures), but this divider is a single band series divider. Also, in [14] by using CRLH-TLs structures, a dual-band 4-way series power divider was presented with low isolation characteristics and poor equal power split.

On the other hand, recently a novel type of metamaterial transmission line has been introduced called simplified composite right and left handed (S-CRLH) transmission line [15,16]. In [16], S-CRLH-TL has been introduced for realizing dual-band applications. It should be emphasized that, the idea of S-CRLH-TL is superior since the structures can be easily designed and engineered to realize the required phase shifters without using the series capacitors. Also, as we know, the implementation of series capacitors (such as integrated capacitors) is difficult, because these capacitors have inherent high frequency parasitic resonance and also cannot achieve larger capacitors. On the other hand, the lumped capacitors may cause great insertion loss along the main transmission line and produce extra and unwanted parasitic effects.

In this paper, based on I-S-CRLH-TL structures, a novel dual-band 4-way parallel power divider is designed and fabricated at two arbitrary frequency bands of $f_1 = 0.95$ GHz (UHF) and $f_2 = 2.4$ GHz (ISM). These two frequency bands are used in radio frequency identification (RFID) technology. However, it should be emphasized that the design procedure and design concept of this paper can be applied to any type of microwave devices. The proposed divider presents excellent isolation and equal power split between output ports in the pass-band. The organization of this paper is as follows: Section II describes theoretical analysis and design methodology leading to dual-band S-CRLH transmission lines. Section III introduces a dual-band 4-way parallel WPD. The simulated and experimental results are discussed in Section III. Finally conclusions

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are made in Section IV.

II. DESIGN THEORY

Figure 1 depicts the unit cell of S-CRLH-TL structure. In Fig. 1, L_R, L_L, C_R and d are series inductance, parallel inductance, parallel capacitance and electrical length of the S-CRLH-TL unit cell, respectively.

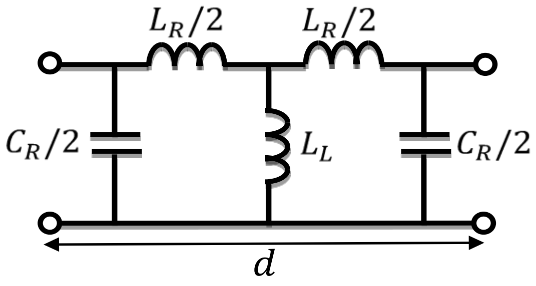


Fig. 1. Circuit model of S-CRLH-TL unit cell.

As can be seen in Fig. 1, unlike the conventional CRLH-TLs, in the S-CRLH-TL structures the series capacitance is removed. Based on Bloch theory, the characteristic impedance and dispersion relation are given by [17]:

$$\gamma(\omega) = \frac{1}{d} cosh^{-1}(A), \tag{1a}$$

$$Z_B(\omega) = \frac{BZ_0}{\sqrt{A^2-1}}, \tag{1b}$$

where ω and $Z_B(\omega)$ are angular frequency and Bloch impedance, respectively. Also, A and B are the elements of the T matrix of the unit cell and can be written as:

$$A = \frac{4L_R+8L_L-4\omega^2 L_R C_R L_L-\omega^2 L_R^2 C_R}{8L_L}, \tag{2a}$$

$$B = \frac{j\omega L_R(4L_L+L_R)}{4L_L}. \tag{2b}$$

Furthermore, in Equation (1), $\gamma = \alpha_s + j\beta_s$, where α_s and β_s are attenuation constant and phase shift constant, respectively. In addition, as we know in the propagation pass-band $\alpha_s = 0$, therefore, Equation (1) can be rewritten as:

$$\beta_s d = \cos^{-1}(A). \tag{3}$$

The above equation shows the characteristic nonlinear phase response of S-CRLH-TLs; therefore, the phase response of these structures can be engineered to produce the desired phase shifts. In this paper, in order to design dual band TLs, a topology of S-CRLH-TLs is considered as shown in Fig. 2, which is known as I-S-CRLH-TLs. This transmission line is composed of two conventional S-CRLH-TL unit cells with input and output conventional TLs at the lateral terminals. It is clear that the total phase shift characteristic of this structure is the superposition of the conventional transmission lines and conventional S-CRLH-TLs. Therefore, for given two frequencies of f_1 and f_2 and two phase shifts of φ_1 and φ_2, the following equations should be satisfied:

$$\varphi_t(f_1) = 2\big(\varphi_s(f_1) + \varphi_{C-TL}(f_1)\big) = \varphi_1, \tag{4a}$$

$$\varphi_t(f_2) = 2\big(\varphi_s(f_2) + \varphi_{C-TL}(f_2)\big) = \varphi_2, \tag{4b}$$

where φ_t is the total phase shift of the proposed structure. Also, φ_s and φ_{C-TL} are the phase shifts of the conventional S-CRLH-TLs and conventional transmission lines, respectively. It should be noted that, based on Equation (3), we can write $\varphi_s = \beta_s d \cos^{-1}(A)$. Moreover, the phase shift of the conventional transmission lines are given by $\varphi_{C-TL} = \beta_{C-TL} l_{C-TL}$. If $\beta_s d = \varphi_{is}$ (i=1,2), then $A = \cos\varphi_{is}$ and therefore, Equation (3) leads to the following equations:

$$\cos\varphi_{1s} = \frac{4L_R+8L_L-4\omega_1^2 L_R C_R L_L-\omega_1^2 L_R^2 C_R}{8L_L}, \tag{5a}$$

$$\cos\varphi_{2s} = \frac{4L_R+8L_L-4\omega_2^2 L_R C_R L_L-\omega_2^2 L_R^2 C_R}{8L_L}. \tag{5b}$$

Solving the above equations for ω_1 and ω_2, it reveals that:

$$\omega_1 = \sqrt{\frac{L_R+\frac{2L_L}{L_R}(1-\cos\varphi_{1s})}{C_R\left(1+\frac{L_R}{4}\right)}}, \tag{6a}$$

$$\omega_2 = \sqrt{\frac{L_R+\frac{2L_L}{L_R}(1-\cos\varphi_{2s})}{C_R\left(1+\frac{L_R}{4}\right)}}. \tag{6b}$$

Now, if $Z_B(\omega) = mZ_0$ (m is an arbitrary constant), by using the Equations (1b) and (2) we can write:

$$\frac{j\omega_1 L_R(4L_L+8L_R)}{4L_L} = m\sqrt{cos^2\varphi_{1s} - 1}, \tag{7a}$$

$$\frac{j\omega_2 L_R(4L_L+8L_R)}{4L_L} = m\sqrt{cos^2\varphi_{2s} - 1}. \tag{7b}$$

Therefore, solving the Equations (5a)-(7b) for given parameter of ω_1, ω_2, φ_{1s} and φ_{2s}, the elements of the proposed structure can be realized. As an example of application, a dual-band stub with $Z_{stub} = 70\,\Omega$ was designed in order to produce phase shifts of $\varphi_1 = +90^0$ and $\varphi_2 = -90^0$ at $f_1 = 0.9\,GHz$ and $f_2 = 2.4\,GHz$, and $m = \sqrt{2}$, respectively. This stub is designed on FR4 substrate with thickness (h) of 0.79 mm, relative permittivity of $\varepsilon_r = 4.4$ and loss tangent of 0.019. Therefore, from Equation (4)-(7), it reveals that $L_L = 11.99\,nH$, $L_R = 2.24\,nH$, $C_R = 2.55\,pF$ and $l_{C-TL} = 14.73\,mm$. The proposed TL were designed in the Agilent Design Systems (ADS) circuit simulator with source termination of $Z_{source} = 50\,\Omega$ and load termination of $Z_{load} = 100\,\Omega$.

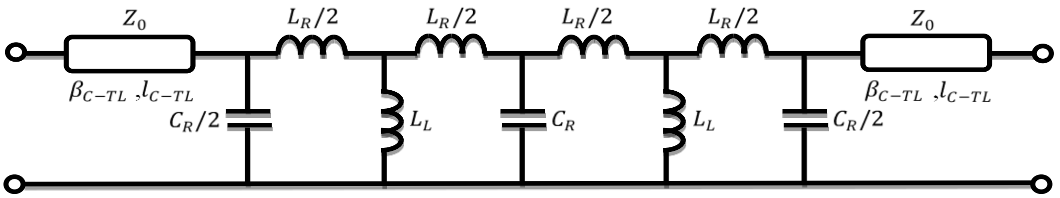
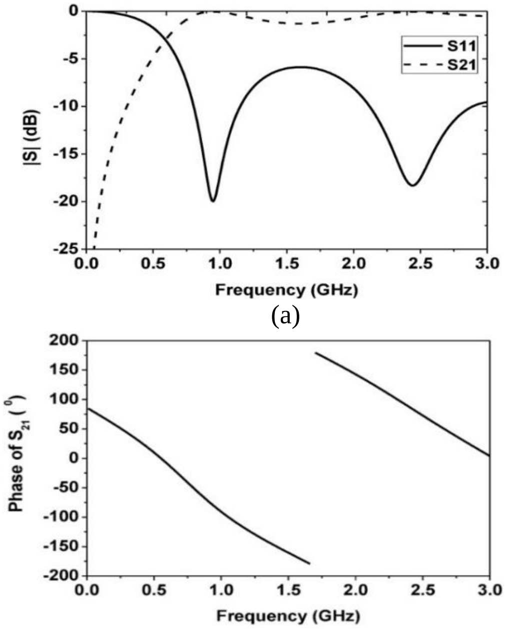


Fig. 2. Circuit model of I-S-CRLH-TLs structure.

Figure 3 displays the S-parameter characteristics of this line. Therefore, these results are distinct proof of the dual-band operation of the designed I-S-CRLH-TL stub.



(a)

(b)

Fig. 3. S-parameter characteristics of the designed I-S-CRLH TLs: (a) return loss and insertion loss, and (b) phase of the insertion loss.

III. DESIGN OF DUAL-BAND WILKINSON POWER DIVIDER

As we know, the classical 2-way WPD consist of two quarter wavelength branch lines with characteristic impedance of $\sqrt{2}Z_o$ and isolation resistor of $2Z_0$, where Z_0 is characteristic impedance of conventional TLs. In order to design 4-way WPD, a 2-way WPD is cascaded with two similar structures at the output ports. Therefore, in order to design a 4-way WPD, six I-S-CRLH transmission lines are required. These lines are designed to produce phase shifts of $\varphi_1 = +90^0$ and $\varphi_2 = -90^0$ at $f_1 = 0.9\,GHz$, and $f_2 = 2.4\,GHz$, respectively. In addition, as we know, the synthesis method for implementation of I-S-CRLH-TLs using microstrip technology has been introduced in [9] and [10], where L_L is implemented by microstrip short circuited stubs and L_R and C_R are realized using microstrip high and low impedance short line elements, respectively. In this proposed structure, two unit cells are shared using a via at top of the structure. This structure is shown in Fig. 4. The proposed 4-way WPD is made up of six dual-band stubs in a square shape configuration. The impedance of these stubs are set to be 70.7 Ω at the design frequencies of $f_1 = 0.915\,GHz$ and $f_2 = 2.440\,GHz$.

The dimensions of these stubs are summarized in Table 1. Finally, the novel 4-way WPD is designed and fabricated. Figure 5 exhibits the fabricated prototype of the proposed divider. Figure 6 exhibits the measured and simulated magnitude of S_{11} for the designed 4-way parallel WPD. As can be seen in this figure, the designed divider can fully cover the desired frequency bands. Moreover, the transmission characteristics to each of the output ports are displayed in Fig. 7. These results demonstrate that the proposed dual-band 4-way WPD splits the input power between output ports equally. The small difference between measured and simulated results can be attributed to small tolerance in substrate permittivity (FR4, $\varepsilon_r = 4.4 \pm 0.2$). Also, the difference between measured and simulated results at high frequency is caused by the extra parasitic capacitance from the input and output ports which were not fully considered during the simulations.

Table 2 compares the physical characteristics and electrical performances of the proposed 4-way WPD with another 4 way power divider presented in [14]. It can be concluded from this table that the designed power divider in this paper provides better input and output return losses, better equal power split and isolation between outputs in both the frequency bands in comparison to [14]. On the other hand, the proposed divider in this paper is fully planar, while the divider presented in [14] is based on the lumped elements.

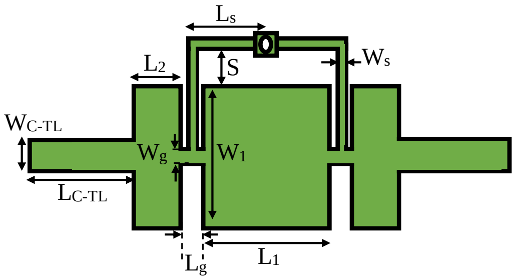


Fig. 4. Symmetrical structure of I-S-CRLH transmission line structure.

Table 1: Dimensions of the dual-band I-S-CRLH-TL structure (Unit: Millimeters)

W_1	L_1	L_1	W_g	L_g
12.41	8.72	4.36	0.85	1.30
L_s	W_s	S	W_{C-TL}	W_{C-TL}
0.45	5.24	0.71	1.38	8.1

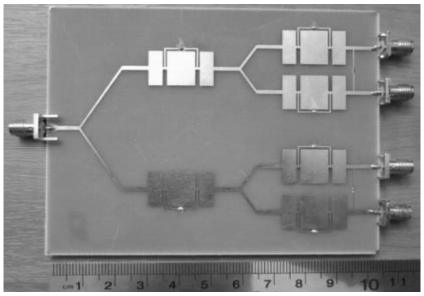


Fig. 5. Fabricated prototype of the proposed dual-band parallel 4-way WPD.

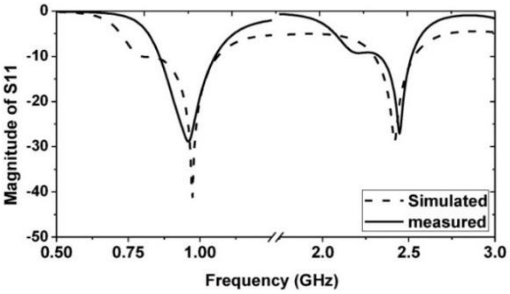
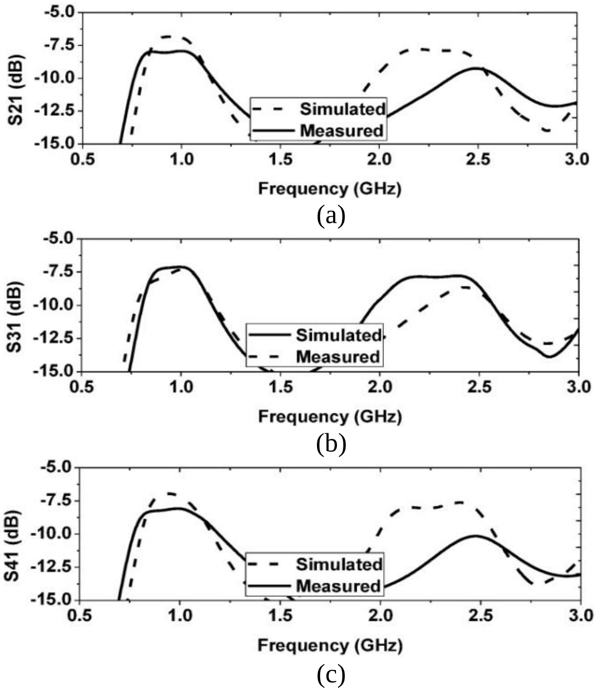


Fig. 6. Magnitude of S_{11} for the proposed dual-band 4-way WPD.



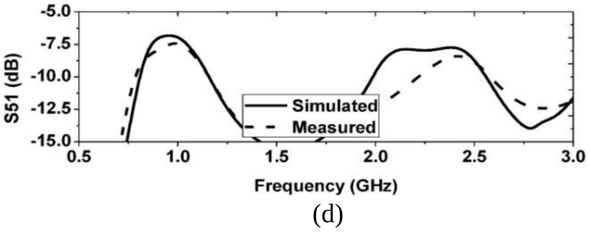


Fig. 7. Transmission characteristics to each of the output ports: (a) S_{21}, (b) S_{31}, (c) S_{41}, and (d) S_{51}.

Table 2: The comparison of the physical parameters and measured performances between proposed 4-way WPD and designed 4-way divider of [14]

			This Work	[14]
Resonance Frequency (GHz)		f_1	0.91	0.91
		f_2	2.44	2.44
Substrate		ε_r	4.4	4.4
		h	0.79	0.79
Circuit Size (λ)		f_1	0.26×0.29	0.23×0.20
		f_2	0.69×0.77	0.62×0.57
Return Loss S_{11} (dB)		f_1	28.8	17.1
		f_2	27.7	22.3
Return Loss S_{22} (dB)		f_1	25.1	15.1
		f_2	23.4	20.4
Return Loss S_{33} (dB)		f_1	24.5	16.5
		f_2	22.7	21.4
Return Loss S_{44} (dB)		f_1	30.4	29.4
		f_2	27.6	23.5
Return Loss S_{55} (dB)		f_1	25.5	23.9
		f_2	24.1	19.9
Insertion Loss (dB)	S_{21}	f_1	7.4	6.8
		f_2	7.7	7.9
	S_{31}	f_1	7.5	6.6
		f_2	8.0	7.7
	S_{41}	f_1	7.4	7.1
		f_2	10.1	7.6
	S_{51}	f_1	7.5	7.2
		f_2	7.9	8.3
Isolation (dB)	S_{32}	f_1	27.3	22.9
		f_2	31.5	35.3
	S_{42}	f_1	34.7	22.4
		f_2	37.4	34.1
	S_{52}	f_1	33.5	21.2
		f_2	35.3	44.7
	S_{43}	f_1	31.5	19.1
		f_2	29.4	26.1
	S_{53}	f_1	32.7	21.2
		f_2	33.5	30.5
	S_{54}	f_1	29.5	22.7
		f_2	28.2	27.8

IV. CONCLUSIONS

In this paper, we presented a novel methodology for designing dual-band 4-way parallel Wilkinson divider. The proposed divider is designed and fabricated on an inexpensive FR4 substrate. The results of the measurements verified the operation of the designed dual-band divider. The dual-band nature of this 4-way divider, close space between output ports and easy integration with planar devices make it a very good candidate for feeding many analog circuits, such as antenna arrays.

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