New design of wideband microstrip branch line coupler using T-shape and open stub for 5G application

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ABSTRACT

A new design of wideband branch-line coupler (BLC) using T-shape with open stub microstrip line is proposed. The branch line coupler is integrated with low and high impedance λ/4 transmission lines to achieve the comparatively compact size of (27.2 mm × 16.5 mm). Operating the bandwidth in simulated of BLC from 2.9 to 4 GHz is obtained 30.22% with a frequency center of 3.5 GHz. Meanwhile, the measured bandwidth of the BLC is cover from 2.8 GHz to 4.22 GHz is equal 33.40% at the center frequency 3.55 GHz respectively. The BLC simulated has low isolation and high return loss of -29.28 dB and -30.69 dB at the center frequency 3.5 GHz. Whereas, the measured result has a simple difference in the return loss and isolation are -27.43 dB and -24.46 dB at the frequency 3.55 GHz respectively. This BLC design has a good coupling factor of -2.97 and insertion loss of -3.65 dB. Furthermore, it obtains an excellent amplitude and phases different between two output of ±0.1 and 93.6°±3.4° with high performance. There is a good agreement between the simulated result and the measured result. This branch line coupler design used for 5G applications for future wireless communication systems.

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1. INTRODUCTION

The branch-line coupler (BLC) is an important component in the microwave integrated circuit such as power divider, modulators, phase shifter and feeding network to beamforming network. It has the ability to divide the power equally/unequally with a 90° phase difference between the output through and the coupled port. The traditional BLC is easily implemented using a quarter-wave transmission line (QWTLs) that includes the impedance of $Zo/\sqrt{2} = 35.35\,\Omega$ and $Zo = 50\,\Omega$ [1]. The conventional BLC single section is realized by the λ/4 microstrip line (QWLMLs) by three lines as 90° transmission lines, one 180° transmission line, one -90° transmission line with specified characteristic impedance [2, 3].

The major issues in conventional BLCs are the large size of λ/4 and the narrow bandwidth of 10%-20% [4] which limits their usage. Many techniques have been proposed to overcome these issues such as using cascading [5] and a T-shaped transmission line, which reduces the size by 55% [6]. The regular microstrip BLC is replaced with a lumped circuit, made from two open stubs by a series of transmission line (TL) [7], and it reduces the size of BLC to 55.2% with a fractional bandwidth of 56% based on the lumped element method, fractal geometry [8], three-section branch-line hybrid [9], a multilayer [10], a meander line [11], and a dual-band branch-line coupler [12]. Various techniques have been employed to miniaturize the size of the microwave component (s), to reduce the BLC size and to increase the bandwidth. Therefore, the size reduction is very important for developing the high-performance radio frequency, and stringent requirements should be in place for the future microwave communication systems [13].

In this study, a compact new design for a wideband BLC using a T-shape and an open stub on the TL is proposed. The transmission line consists of a horizontal open-stub with a slot of T-shape and a vertical T-shape connected to the center of the TL. The symmetrical T-shape transmission line is one of the best methods to realized microwave as in [14]. The proposed BLC wideband (QWTL) structure hasthe capability to achieve a wideband frequency ratio operation. The overall proposed structure is simulated by using CST Microwave Studio and fabricated using a cheap substrate material of FR-4. A good agreement between the simulation and measurement results was obtained throughout the 2.9 to 4 GHz frequency band.

2. THEORETICAL ANALYSIS TRANSMISSION LINE

2.1. Mixed-mode S-parameters of the BLC

In this part, scattering parameters integrated with the ABCD matrix of the circuit proposal were employed to obtain the analysis solution as SSB, SSE and SSD are to describe the S-parameters as in [15]. The proposed branch-line coupler (BLC) is a single section consisting of four ports, and the stander scattering matrix [S^{BLC}] can be expressed as follows:

$$[S^{BLC}] = \begin{bmatrix} S_{11} & S_{12} & S_{13} & S_{14} \\ S_{21} & S_{22} & S_{23} & S_{24} \\ S_{31} & S_{32} & S_{33} & S_{34} \\ S_{41} & S_{42} & S_{43} & S_{44} \end{bmatrix} \quad (1)$$

The relationship between the mixed-mode [S^{MD}] and the scattering matrix [S^{BLC}] of the proposed branch-line coupler (BLC) has been reported as in [15].

$$[S^{MD}] = [MT]\,[S^{BLC}]\,[MT^{-1}] \quad (2)$$

$$[\mathrm{S}^{\mathrm{MD}}] = \frac{1}{2}\begin{bmatrix} S_{11} - S_{21} - S_{12} + S_{22} & S11 - S_{21} + S_{12} - S_{22} & & \\ S_{11} + S_{21} - S_{12} - S_{22} & S_{11} + S_{21} + S_{12} + S_{22} & & \\ \sqrt{2}\,(S_{31} - S_{32}) & \sqrt{2}\,(S_{31} + S_{32}) & 2S_{33} & 2S_{34} \\ \sqrt{2}\,(S_{41} - S_{42}) & \sqrt{2}\,(S_{41} + S_{42}) & 2S_{43} & 2S_{44} \\ \sqrt{2}(S_{13} - S_{23}) & \sqrt{2}(S_{14} - S_{24}) & & \\ \sqrt{2}(S_{13} - S_{23}) & \sqrt{2}(S_{14} - S_{24}) & & \end{bmatrix} \quad (3)$$

The matrix equation [MT] is a standard of S-parameters used in the proposed BLC and can be expressed as follows:

$$[\mathrm{MT}] = \frac{2}{\sqrt{2}}\begin{bmatrix} 1 - & 1 & 0 & 0 \\ 1 & 1 & 0 & 0 \\ 0 & 0 & \sqrt{2} & 0 \\ 0 & 0 & 0 & \sqrt{2} \end{bmatrix} \quad (4)$$

3. STRUCTURE OF PROPOSED BLC USING T-SHAPE AND OPEN STUB TL

The quarter wavelength of the transmission line BLC is known to have a narrow bandwidth and bulky size, as shown in Figure 1(a), the size of the branch-line coupler (BLC) considering the major issues. Figure 1(b) shows the Z_0 as well as the θo characteristic impedance and the electrical length of the BLC. The layout of the symmetrical T-shape TL, consists of two series transmission lines (Za1, θa1) and the shunt-open stub (Z_{b2}, θ_{b2}). The design equation of the T-shape model is given by [16] and can be expressed as follows:

$$Z_{a1} = Z \cot \frac{\theta_{a1}}{2} \quad (5)$$

$$Z_{b1} = \frac{Z_{a1}}{2} \tan\theta_{a1} \tan\theta_{b2} \quad (6)$$

Z is the characteristic impedance Ω of the BLC. The T-shape model BLC achieves a compact size when θa1 is <90°. However, when the series arm impedance Z_{a1} increases, the series arm length θa1 will decrease, while the shunt impedance Z_{b1} decreases for a constant stub length θ_{b1}. The present equivalent circuit of the conventional branch-line coupler is depicted in Figure 1 (c) and Figure 1(d).

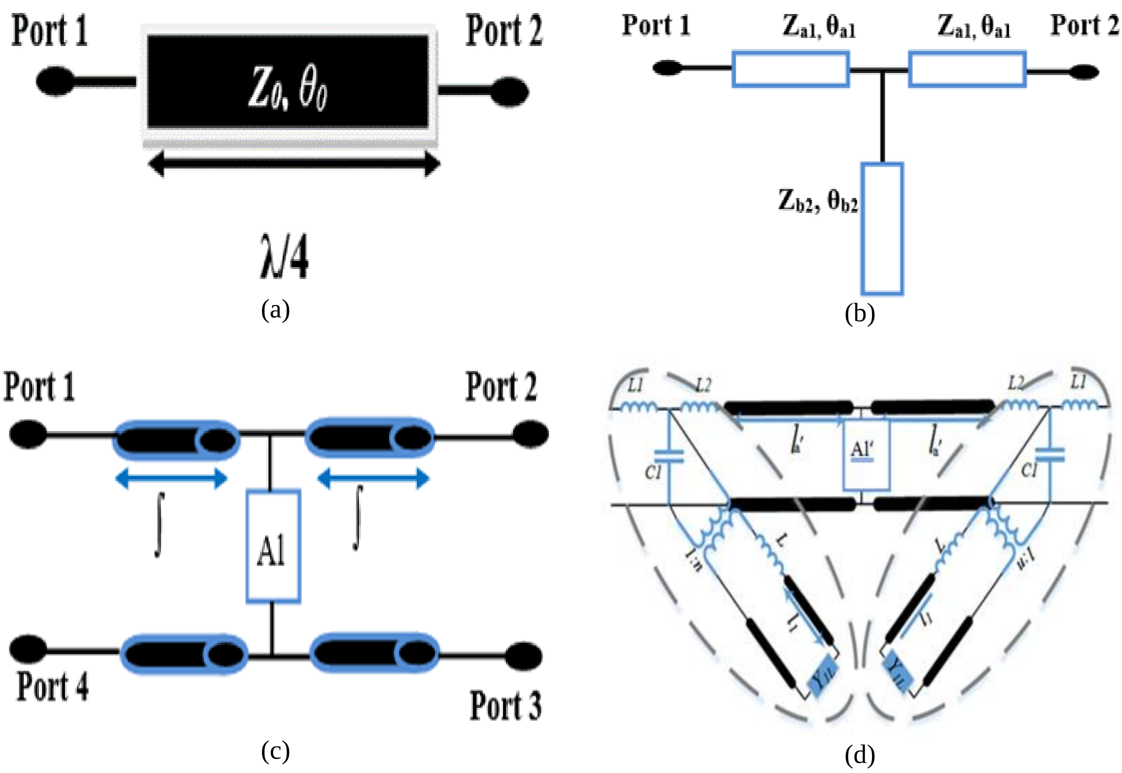

Figure 1. (a) Formal 90° branch-line coupler, (b) equivalent circuit of λ/4 transmission line T-shape model, (c) conventional transmission line, (d) equivalent circuit of the quarter wavelength λ/4 transmission line

The scattering parameters of the four-BLC ports, S_{11}, S_{21}, S_{31}, S_{41}, are expressed in term of even and odd reflection coefficients Γ_{ee}, Γ_{eoo}, Γ_{ooe} and Γ_{oo} which can be expressed as follows:

$$S_{11} = \frac{\Gamma_{ee} + \Gamma_{oee} + \Gamma_{oo} + \Gamma_{eoo}}{4} \quad (7a)$$

$$S_{21} = \frac{\Gamma_{ee} - \Gamma_{oee} - \Gamma_{oo} + \Gamma_{eoo}}{4} \quad (7b)$$

$$S_{31} = \frac{\Gamma_{ee} - \Gamma_{oee} + \Gamma_{oo} - \Gamma_{eoo}}{4} \quad (7c)$$

$$S_{41} = \frac{-\Gamma_{ee} - \Gamma_{oee} + \Gamma_{oo} + \Gamma_{eoo}}{4} \quad (7d)$$

The characteristic impedance, for example Z_0=50 Ω, Z_1=139.7 Ω, Z_2=54 Ω, Z_3=58.3 Ω and electrical length $\theta_1=\theta_2=\theta_3$=90° [17]. The BLC single section is printed on the substrate from FR-4, ε_r=4.4, loss tangent, tan δ=0.025, and h=1.6 mm. The primary resistances of the main-line of the BLC are Z_1, Z_2, and Z_3. The electrical length θ_1, θ_2, and θ_3 is the main-line for BLC. Port 1 is an input, port 2 and port 3 are outputs, while port 4 is an isolation port. The width of the microstrip transmission line at 3.5 GHz at the center frequency was calculated from the (8) and can be expressed as follows:

$$W = \begin{Bmatrix} \frac{8h\,e(A)}{e\,(2A)-2} & \text{for } \frac{W}{h} < 2 \\ \frac{2h}{\pi}\begin{Bmatrix} B-1-\ln(2B-1)+\frac{\varepsilon r-1}{2\varepsilon r} \\ \left[In\,(B-1)+0.39-\frac{0.61}{\varepsilon r}\right] \end{Bmatrix} & \text{for } \frac{W}{h} > 2 \end{Bmatrix} \tag{8}$$

Where

$$A=\frac{Z_N}{60}\sqrt{\frac{\varepsilon r+1}{2}}+\frac{\varepsilon r-1}{\varepsilon r+1}\left(0.025+\frac{0.11}{\varepsilon r}\right) \tag{9}$$

$$B=\frac{376.73\,\pi}{2z_n\sqrt{\varepsilon r}} \tag{10}$$

Z_N is the impedance characteristic of the microstrip line and the subscript N refers to the number of ports; 0, 1, 2, and 3. The length of the microstrip transmission line from the quarter wavelength λ/4 of the BLC has been reported in [1] and was calculated from the (11), which can be expressed as follows:

$$L=\frac{c}{4f_0\sqrt{\varepsilon_{eff}}}-0.412\,h\left[\frac{\varepsilon_{eff}+0.3)\,(\frac{W}{h}+0.264)}{\varepsilon_{eff}-0.258)(\frac{W}{h}+0.8\,)}\right] \tag{11}$$

The velocity of light in space is c=186, 282 miles per second, and the effective permittivity $\varepsilon_{eff,}$ of the BLC microstrip line, was obtained as in [18] and can be expressed as follows:

$$\varepsilon_{eff} = \begin{Bmatrix} \frac{\varepsilon r+1}{2}+\frac{\varepsilon r-1}{2}\left[\frac{1}{\sqrt{1+\frac{12h}{w}}}+0.04\left(1-\frac{W}{h}\right)2\right] & for\ W/h \le 1 \\ \frac{\varepsilon r+1}{2}+\frac{\varepsilon r-1}{2}\left(\frac{1}{\sqrt{1+12h\,/W}}\right) & for\ W/h > 1 \end{Bmatrix} \tag{12}$$

Through the even-odd mode analysis, S-parameters of the reflection coefficient to the transmission line (TL) can be expressed in [19]. Γ is the reflection coefficient and T is the transmission line coefficient, meanwhile can be expressed as follows:

$$\Gamma=\frac{a'+\frac{b"}{Z_0}-CZ_0-d}{a'+\frac{b"}{Z_0}+CZ_0+d} \tag{13}$$

$$T=\frac{2}{a'+\frac{b"}{Z_0}+CZ_0+d} \tag{14}$$

4. PROPOSED DESIGN BLC WITH T-SHAPE AND OPEN STUB

To overcome the major issues of the narrow bandwidth and the bulky size of the BLC, the proposed T-shape and an open stub were used to replace a conventional λ/4 of the transmission line. Figure 2 shows the simulated design of the proposed BLC where a compact design T-shape and an open stub were used. As shown in Figures 2(a) and (b), T-shaped slots were introduced to replace a conventional (QWTL) BLC design. In the proposed design layout, the author also introduced the equivalent open stub design with an open stub with a T-shape model and T-shape model structure to the proposed layout in order to give a better performance in the designas shown in Figure 2(c) and (d). The T-shape approach was adopted to reduce the size of the transmission line λ/4 and miniaturize the microstrip of the BLC. The impedances of the horizontal and vertical of the branch-line coupler (BLC) are 35.36 Ω and 50 Ω. Meanwhile, the output of the phase difference of the quadrature wavelength of the BLC is 90°, and the electrical length of the BLC is θ2=θ3=90°. All the impedances and optimized parameters for the BLC are presented in Figure 2.

The Agilent vector network analyzer was used to test the performance of the proposed BLC while as to ensure that the proposed BLC design achieved good performance and was compared with the simulated result. Figure 3 shows the experimental setup for the S-parameters measurement setting of the proposed BLC. The network analyzer was used to measure S_{11}, S_{21}, S_{31}, and S_{41} with a frequency ranging from 2 GHz to 5 GHz. Table 1 presents all dimensions of the proposed BLC.

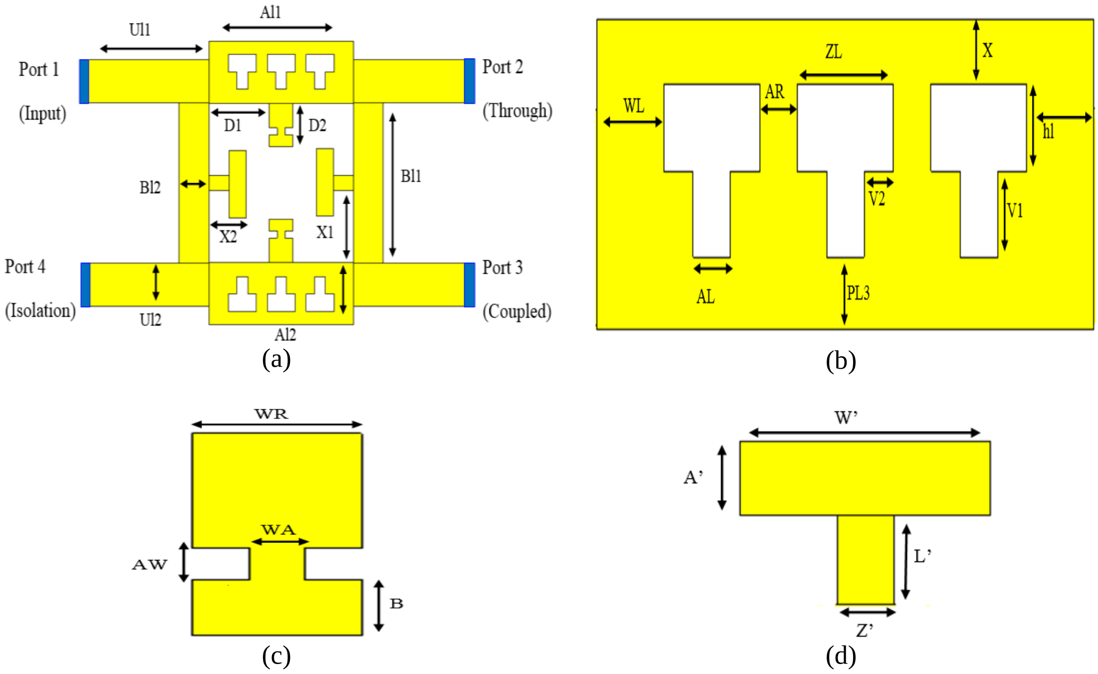

Figure 2. The simulated design of the proposed BLC, (a) layout of branch-line coupler compact size, (b) equivalent T- shape slot structure, (c) equivalent open stub with T- shape model, (d) equivalent T- shape model structure

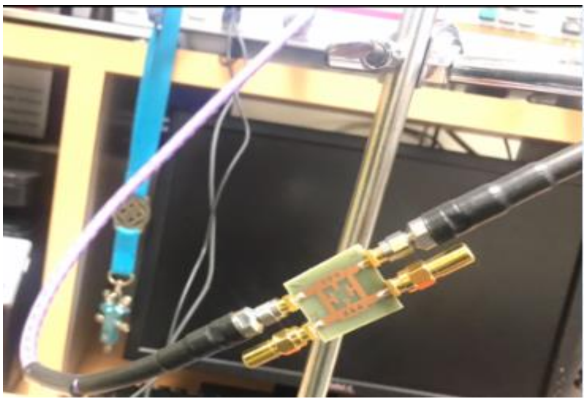

Figure 3. Photograph of BLC under test S-parameters

Table 1. The dimension of the proposed branch-line coupler with T-shape model all dimension (mm)

Parameters	Value	Parameters	Value
Z1	35.36Ω	V1	1
Z2	50.00Ω	V2	0.55
θ_1	90°	AR	0.7
θ_2	90°	AL	0.7
θ_3	90°	WL	1.28
Al1	9.4	PL3	0.93
Al2	3.5	X	1.46
Bl1	9.3	h	1
Bl2	1.9	WR	1.5
Ul1	8.9	B	0.69
Ul2	2.5	AW	0.41
D1	3.9	WA	0.5
D2	2.5	W'	3.9
X1	4.19	A'	1.1
X2	2.83	L'	1.31
ZL	1.8	Z'	0.87

5. DESIGN I

As for the design (I) showed in Figure 4, the author had designed a conventional BLC by using all the calculated parameters obtained through the (11) for obtaining the length of TL and the (8) in obtaining the width of TL. All of the parameters were obtained by tuning the center frequency at 3.5 GHz and by using the characteristic of the material used which is FR-4. The final dimension obtained is as follows: A1=10 mm, A2=4.5 mm, B1=10.3 mm, B2=2.5 mm, C1= 0 mm, C2=2.5 mm. The occupied area of the proposed coupler is of the design (I) is 0.29 λg×0.17 λg (29×17 mm^2). The simulation result of design (I) is presented in Figure 5. The results show that the differential mode impedance matches, where the return loss S_{11} value is -26.4 dB at the 3.4 GHz operating frequency and their isolation S_{41} value are -28.68 dB at the 3.43 GHz. Additionally, the coupling factor S_{21} of design (I) and the insertion loss S_{31} is equal to -3.5 dB and -3.1 dB, respectively. Figure 5 also shows that the fractional bandwidth is 24.42% from 2.9 GHz to 3.7 GHz. Figure 6 shows the measured phase difference between the output ports through S_{21} and coupled S_{31}. It indicates that design (I) is able to couple the signal diagonally from the input to the output at 3 GHz.

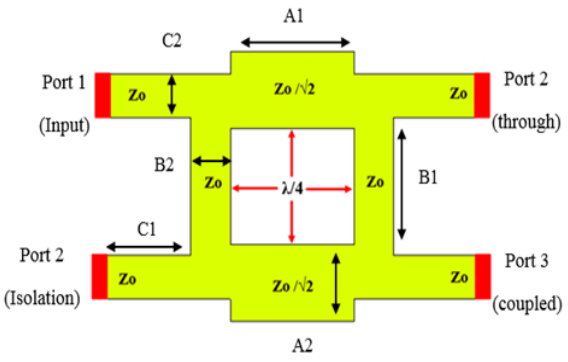

Figure 4. Conventional structure for branch-line coupler

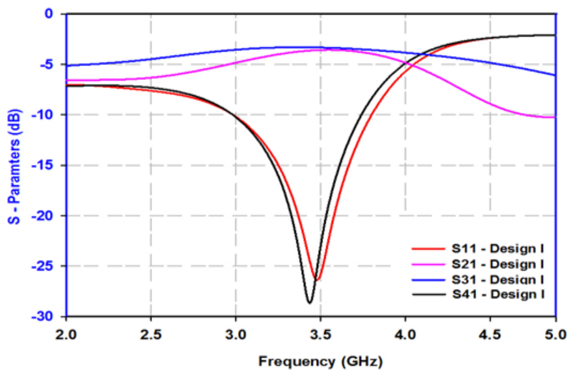

Figure 5. The conventional frequency response of the BLC S11, S21 S31 and S41

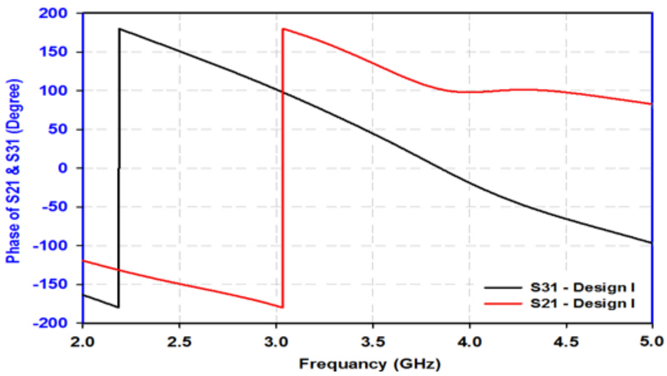

Figure 6. The phase of the design (I) BCL between S21 and S31

6. DESIGN II

Design (II) is the response of the microstrip BLC using the slot T-shape and an open stub with high and low impedance wavelength on the horizontal wavelength transmission line 35.36 Ω as discussed in the previous section (3). Clearly, the proposed BLC enhances the bandwidth for the impedance matching in design (II) through the implementation of the T-shape and the open stub techniques. From Figure 7, the value of the return loss S_{11} for the proposed design is -30.69 dB at the center frequency of 3.5 GHz. This figure also indicates that the isolation factors obtained at the operating frequency of 3.5 GHz band is equal to -29.28 dB. Additionally, the coupling factor S_{21} and the insertion loss S_{31} of the proposed design are at -2.97 and -3.65 dB, respectively. From the result shown in Figure 7, the introduction of the T-shape and the open stub in the proposed design wide the bandwidth value, wherein this design the fractional bandwidth is 2.9 GHz-4 GHz, which is equal to 32.29%. This data clearly indicates that the introduction of the slotting and the stub techniques within the BLC design can widen the bandwidth value. The bandwidth was calculated using (15) and can be expressed as follows:

$$\text{Bandwidth (BW)} = \frac{f_2 - f_1}{\sqrt{f_2 \times f_1}} \times 100\ \% \tag{15}$$

The simulated result of the proposed design (II) has a good agreement on the frequency of 3.5 GHz. Figure 8 shows the different phases of two output ports, S_{21} and S_{31} of the proposed BLC. Figure 9 shows the measurement result of the proposed design (II). The results signify that the range operating bandwidth is between 3 GHz to 4.1 GHz where it gives 31% bandwidth values, where the return loss S_{11} and isolation S_{41} are -27.47 GHz and -26.2 GHz respectively. Meanwhile, the through S_{21} and coupled S_{31} values are equal to -4.4dB and -4.1dB, respectively. Figure 10 shows the fabricated proposed BLC using the T-shape with the open stub.

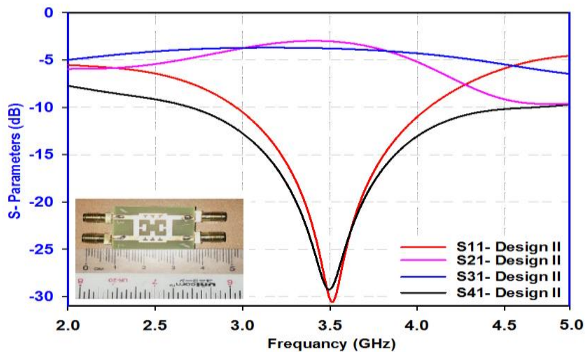

Figure 7. The simulation frequency response of the proposed branch-line coupler S11, S21, S31, S41

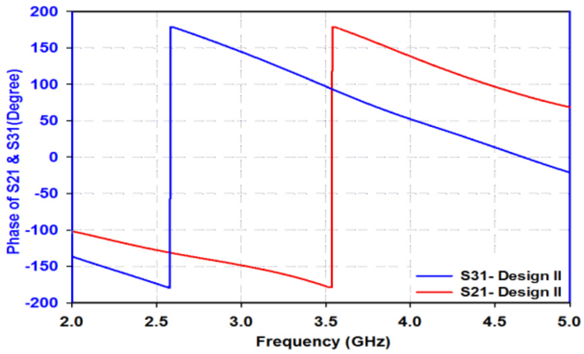

Figure 8. The phase of the design II of two output ports S21 and S31

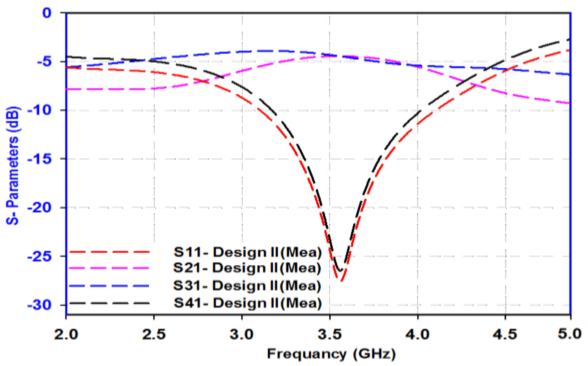

Figure 9. The measurement result of the proposed design II

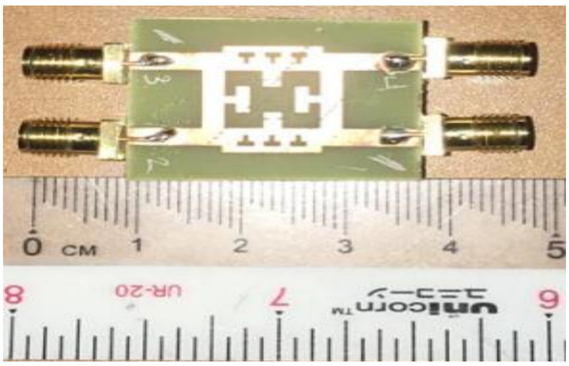

Figure 10. Fabrication of the proposed BLC

7. VALIDATION

7.1. Comparison between design (I) and desin (II)

This section discusses the comparison structure analysis of the single section of design (I) and design (II) of the BLC. Figure 11 shows the difference between the conventional design (I) and the proposed design (II), using the techniques of the T-shape and the open stub on the horizontal and vertical arm transmission lines of design (II). Moreover, the results show that the fractional bandwidth has been improved from 24.42% to 32.29% and the shifting of the signal from the frequency 3.43 GHz to 3.5 GHz as a desired operating frequency. The results of the coupling factor between two ports, S_{21} and S_{31} for the conventional design (I) and the proposed design (II) increased from (-3.5 and -3.1) dB to (-2.97 and -3.65) dB respectively, as shown in Figure 12. As for Figure 13, it demonstrates a simulation for the conventional design (I) and the proposed design (II) of the phase difference between ports S_{21} and S_{31} respectively.

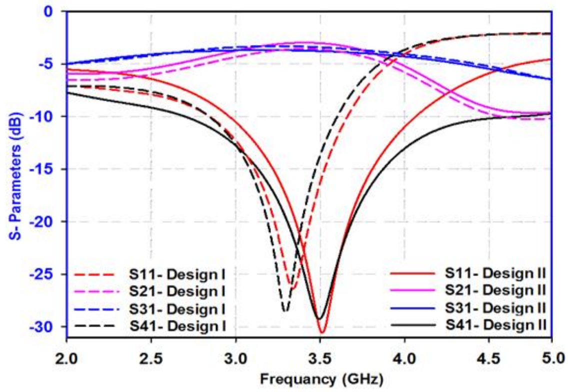

Figure 11. Comparison of the design (I) and design (II)

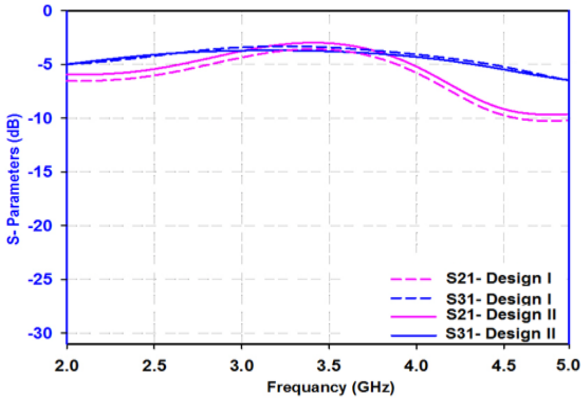

Figure 12. Comparison of the coupling factor (S21 and S31) of the design (I) and design (II)

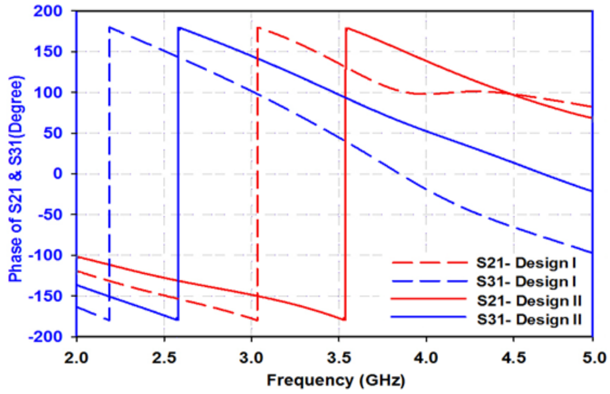

Figure 13. Comparison phase of the design (I) and design (II) for (S21) and (S31)

7.2. Comparison of the simulation and measurement result in the proposed design (II)

The comparison of the simulation and measurement result of design II is shown in Figure 14. According to the result shown, it was interpreted that the simulated and measured data is in good agreement. Figure 15 shows that the amplitude imbalance and the phase difference between two output ports for the simulation and measurement are approximately ±0.1 dB and 90°±3.54° and 90°±3° respectively.

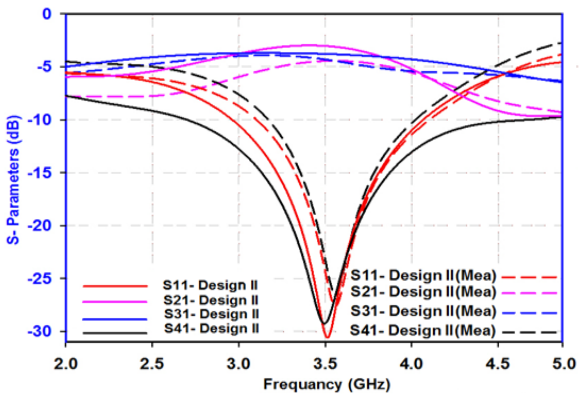

Figure 14. Comparison of the simulation and measurement for design (II)

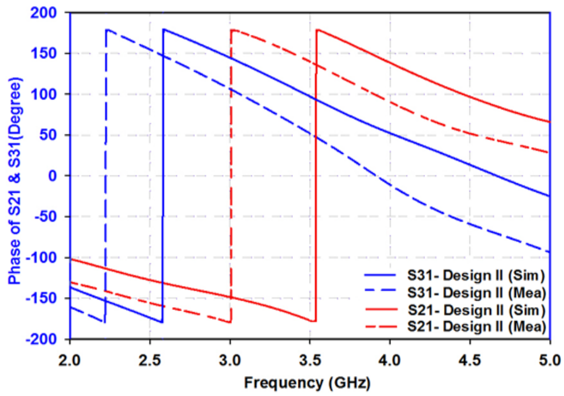

Figure 15. Comparison phase of the simulation and measurement for design (II)

7.3. Comparison of the simulation design (I) design (II) and measurement design (II)

This section shows a comparison of the simulation and measurement between design I and design (II) as shown in Figure 16. While Table 2 shows a comparison of the conventional design I and proposed design (II). All the data from Figure 16 is tabulated in Table 2. As can be seen, the proposed design gives a better return loss S11 and isolation S41 values where it gives -30.69 dB and -29.28 dB at center frequency 3.5 GHz. The table also clearly shows the effect of T-shape and stub techniques on miniaturizing the size of the proposed design. Table 3 shows a comparison of the proposed BLC design performance with previous researches in terms of their isolation, return loss, coupling factor, insertion loss, and phase shift values respectively. This table shows that the proposed BLC design is comparable with previous work although the proposed design implementing less complex structure.

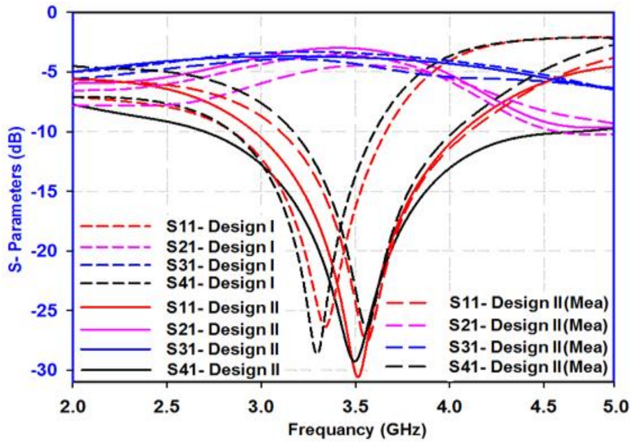

Figure 16. Comparison of the simulation design (I) design (II) and measurement design (II)

Table 2. Comparison of the conventional design (I) and proposed design (II)

Parameters	Frequency f_o (GHz)	Return loss (S_{11})	Through (S_{21})	Coupled (S_{31})	Isolation (S_{41})	Bandwidth (dB)	Size (λ_g×λ_g)
Design I	3.4	-26.4	-3.5	-3.1	-28.4	24.42%	0.29 λ_g×0.17 λ_g
Design II (simulation)	3.5	-30.69	-2.97	3.65	-29.28	32.29%	0.27 λ_g×0.16 λ_g
Design II (Measurement)	3.55	-27.47	-4.4	-4.1	-26.2	31%	

Table 3. Comparison of the previous state to the BLC conventional design (I) and proposed design (II)

Ref	Technology	Frequency (GHz)	S_{11} (dB)	S_{21} (dB)	S_{31} (dB)	S_{41} (dB)	Phase shift
[6]	Dual feed and T-shape	3	21	1.02	-	22	90°
[20]	T-model	2.5	34.68	3.45	3.79	23.1	90.9°
[21]	T-model with open stubs	2.45	21.7	3.2	3.1	36.6	0.1
[22]	LC-model	2.4	29	3	3.08	30	0.037°
[23]	Microstrip line	3	16.3	1.0	0.25	18.7	90°
[24]	Meander T-shape line	2.1	46.9	3.08	3.19	35.6	-
[25]	Spirals and Step Impedance	3	17	3.02	3.16	34	0.49°
This work (Design I)	Conventional	3.34	27.47	4.4	4.1	26.2	90°
This work (Design II)	T-shape + open stub	3.5	30.69	2.97	3.65	29.28	90°

8. CONCLUSION

This paper proposed a compact new design for a single-section wideband 3-dB BLC with a vertical slot T-shape on the TL connected with two open-stubs and a horizontal print T-shape quarter wavelength transmission line. The proposed BLC was designed using the right/left-handed transmission line. The design I of the BLC was a conventional design as validation with the enhanced structure in design (II). The proposed design (II) had the compact size of 27×16 mm (0.27 λg×0.16 λgmm^2) and improved the bandwidth from 24.42% to 32.29%. The results showed that the simulation and measurement of return loss, insertion loss and phase shift between ports had a good agreement with design (II) BLC λ/4 transmission line. The application of the proposed BLC design in this study can be used for future studies in the 5G wireless communication system.

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