A compact microstrip coupler using T-shape and open stubs for fifth generation applications

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Abstract. The paper presents a new design of a compact branch-line coupler (BLC) operating at 3.5 GHz, that is suitable for 5G applications. In order to miniaturize the proposed coupler, two miniaturization methods are combined where a T-shaped structure is used instead of quarter wavelengths parallels, as well as open stubs are introduced into the series lines resulting in a size reduction of 52.56% with 25.05% fractional bandwidth (FBW). The frequency responses indicate that the presented coupler is able to operate at 3.04 GHz to 3.91 GHz with a low return loss and high isolation that is improved to -28.9 and -31.1 dB in 3.5 GHz, insertion loss and coupling of -3.6 dB and -3.5 dB, respectively, and a phase difference of about 90°±1°. The strong agreement of measurement and simulation results indicated the suitability of this proposed design for 5G microwave integrated circuits (ICs) that require a small size.

1 Introduction

The branch-line coupler (BLC) is a very helpful basic circuit for splitting and combining quadrature signals. Furthermore, it is extremely important element in the realization of various circuits [1]. For example, it can be utilized as component of a mixer in microwave integrated circuits [2], or it may be used as a power splitter in phase shifters, modulators and beamforming systems in antenna arrays. In effect, BLC is extensively realized through the use of stripline [3], multilayer [4], microstrip [5], and finite-mass coplanar waveguides [6] structures. The BLC uses a quarter-wave transformer to create a basic square-shaped pattern to be used for dividing or combining power. But, at lower frequencies, the conventional branch line size is excessively large in the PCB. Its physical size is relatively driven by the wavelength that is large at low frequency, and consistently affects the size of the quarter-wavelength (λ/4) transmission lines that are used. Still, currently, movable devices need compact element sizes and less precious features. Accordingly, high performance, small size, and inexpensive are frequently the strict conditions that must be emphasized in meeting the conditions of ultramodern wireless communication devices (7). Various approaches are used to overcome these problems and to minimize the coupler implementation, as for examples, in [8], the minimization of the size is obtained using quasi-lumped elements, a periodic capacitive load and a lumped circuit, consisting of two stubs opened with a series of transmission lines (TL) [9], T-shaped structures [10][11], slow wave lines [12], fractal structures [13], high-resistance lines [14], interdigitated capacitors [15], artificial transmission lines [16], the use of cascading [17], a multilayer [18], a meandering line [19], low-pass filters and planar cells [20] [21] [22] and a radial stub [23].In this paper, by combining two miniaturization methods, the compact design of the microstrip coupler is explored and further size reduction is achieved. The proposed coupler layout is adapted for operation with a center frequency of 3.5 GHz. The proposed technique uses a T-shape to make a parallel λ/4 transmission line equivalent circuit. Then the open stubs are introduced in the horizontal transmission lines to improve the miniaturization, the adaptation and isolation of the proposed coupler. The proposed miniaturization technique offers good size minimization compared to the conventional one, and also takes into account the BLC performance and its ability to split the input signal without limiting the coupling power.

2 Conventional branch-line coupler

As in figure 1, a conventional BLC was designed using the TL theoretical study results detailed in [10]. By adjusting the frequency center to 3.5 GHz and employing of the properties of the material employed, namely FR-4 (ε_r=4.4, h=1.6 mm and tan(δ)= 0.025), all conventional BLC dimensions are obtained and listed in table1. The surface area occupied by the conventional coupler is (32mm x 20mm) and simulation frequency responses are shown in figure 2 and figure 3, where the return loss S_{11} and isolation S_{41} are -20.1 dB and -26.1, respectively at the resonance frequency of 3.5 GHz. In addition, the coupling factor S_{31} and insertion loss S_{21} are

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equal to -3.7 dB and -3.8 dB, respectively, with an output ports phase difference of 88.97°. The result also indicates that the fractional bandwidth is 30% from 3.1 GHz to 4.2 GHz.

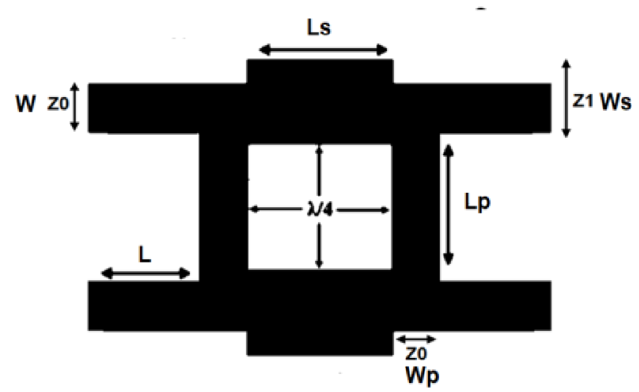


Fig. 1. Conventional branch-line coupler design

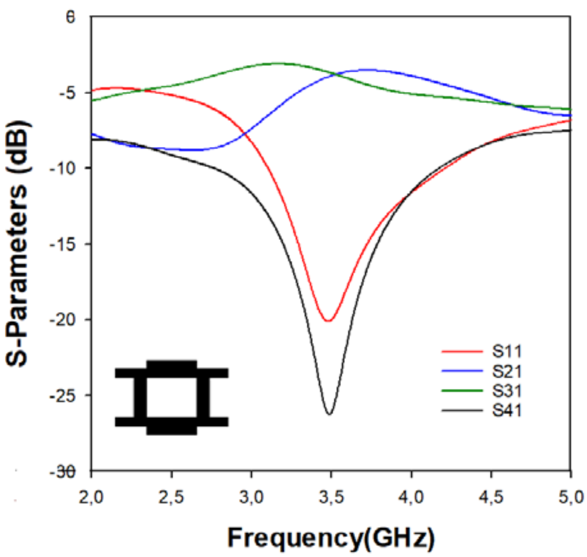


Fig.2. Conventional BCL frequency response

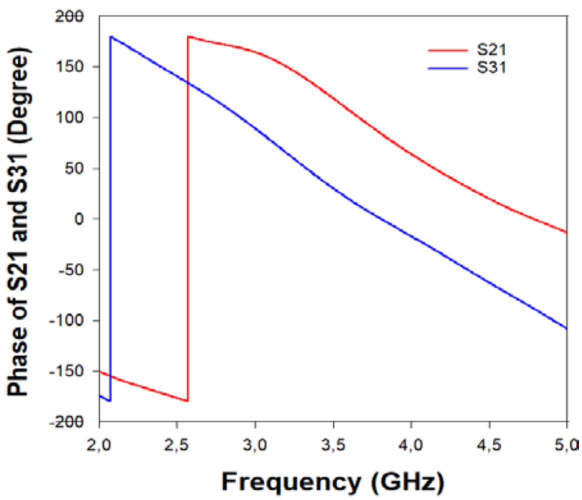


Fig.3. Phase of two output ports of the conventional BCL

Table 1. Conventional branch-line coupler parameters

Parameters	Value (mm)
z_0	50
z_1	35.7
Ls	10
ws	1.5
Lp	10.03
wp	2.5
L	8.5
w	2.5

3 Miniaturization of BLC

3.1 T-shaped structure

To miniaturize the conventional BLC presented in figure 1 and improve its performance, the quarter-wave series TLs are transformed into their equivalent T-shaped structure, like illustrated in figure 4. The characteristic impedance and the electrical length of the conventional BLC arms are Z_S and θ, respectfully. This approach reduces the quarter wavelength transmission lines and to allows the miniaturization of the conventional BLC microstrip.

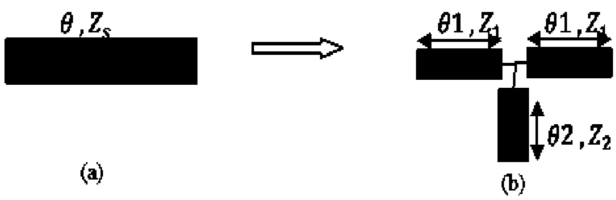


Fig.4. Equivalent T-shape structure: (a) λ/4 transmission line, (b) equivalent T-shaped structure

By defining the set $Z_S \equiv [Z_1, Z_2]$ and $\theta \equiv [\theta_1, \theta_2]$, the equivalent T-shaped form is illustrated in figure 4. To connect the two patterns shown in Figures 4(a) and 4(b), we use the equation for the ABCD matrices which is given by:

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix}_{\lambda/4} = \begin{bmatrix} 0 & jZ_s \\ jY_s & 0 \end{bmatrix} \qquad (1)$$

Were

$$A = D = 1 + Z_1/Z_2,$$

$$B = Z_1\left(2 + \frac{Z_1}{Z_2}\right)$$

$$C = 1/Z_2$$

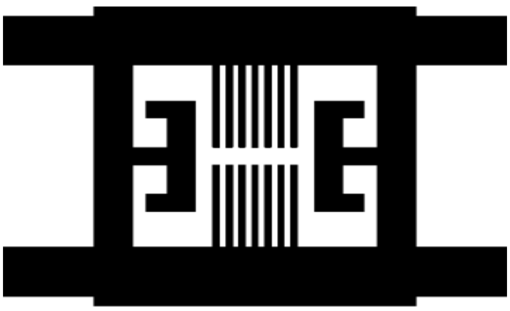
The reduced line electrical lengths are represented as the set $[\theta_1, \theta_2]$. On the basis of the T-model expression described in detail in [21], we can formulate the miniaturized coupler design equations presented in Equation (2) and Equation (3).

$$Z_1 = \frac{Z_S}{tan\theta_1} \qquad (2)$$

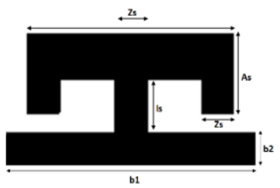
$$Y_2 \tan\theta_2 = \frac{2}{Z_1 tan2\theta_1} \qquad (3)$$

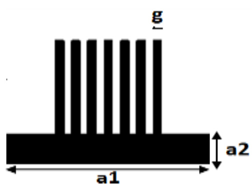
3.2 Compact size branch-line coupler

To overcome the major issue of bulky size of the BLC, the described BLC λ/4 segments are converted into their respective T-shaped section and then the open stubs will be introduced into the series section to improve the proposed coupler's performance. in Table 2, the proposed design values are given and in figure 5 its construction is shown. The T-shaped branch-line coupler is simulated by means of the CST simulators, for which the S-parameters are presented in figure 6. The global area of the T-shaped BLC is (19.6mm*15.5 mm), so it occupies 47.44% from the conventional one, therefore it achieves an area savings of 52.56%. The return loss S_{11} and isolation S_{41} are respectively -28.9 dB and -31.1dB in the resonant frequency, the bandwidth covered from $f_1 = 3GHz$ till f_2=3.9 GHz resulting in a fractional bandwidth of 25.05%. The S_{21} and S_{31} are -3.6 dB and -3.5 dB in the same frequency band. Figure 7 shows the difference in phase between the output ports by S_{21} and S_{31} which is equal to 89 ° which is nearly to 90 °. This indicates that the proposed design can diagonally couple the signal from the input to the output at 3.5 GHz.



(a) Design of the proposed branch-line coupler





(b) Equivalent T-shape structure **(c)** Equivalent open stub

Fig.5. Design of the proposed branch-line coupler

Table 2. Proposed branch-line coupler dimension

Parameters	Value
a_1	9.4
a_2	3
b_1	9.3
b_2	1.5
c_1	5.1
c_2	2.5
zs	0.87
ls	1.31
As	1.1
g	0.25

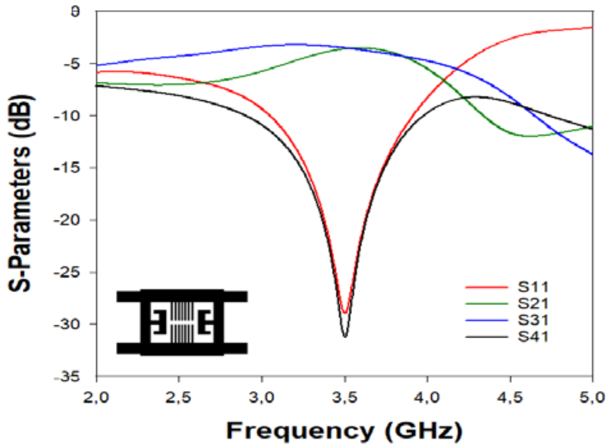


Fig.6. Frequency response of the proposed branch-line coupler

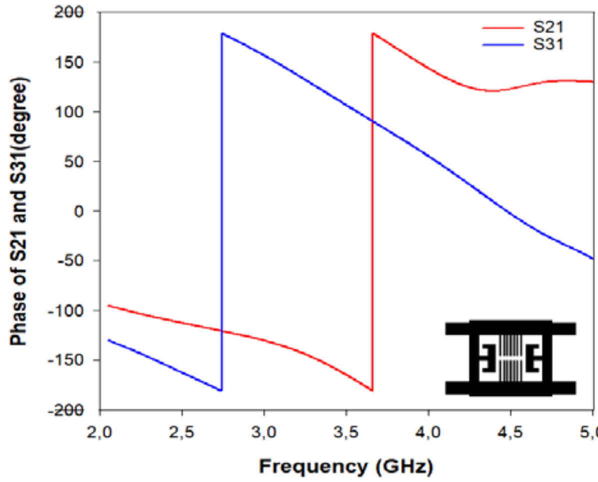


Fig.7. Phase of two outputs ports of the proposed BLC

A prototype of the optimized hybrid quadrature coupler has been fabricated, as illustrated in figure 8, where the small coupler size is 19.6mm*15.5mm, which is 52.56% smaller than the conventional coupler. The frequency responses results of the proposed design are shown in Figure 9, where our fabricated structure shows good results around the resonant frequency and good agreement with the simulation results. Additionally, figure 9 also illustrates a bandwidth that becomes 14.4% from 3.29 GHz to 3.81 GHz. The measured phase difference between the two output ports $S_{21}$and $S_{31}$is equal to 87.9%, which indicates that the proposed design is suitable for diagonal coupling of signals from its input to its output at 3.56 GHz.

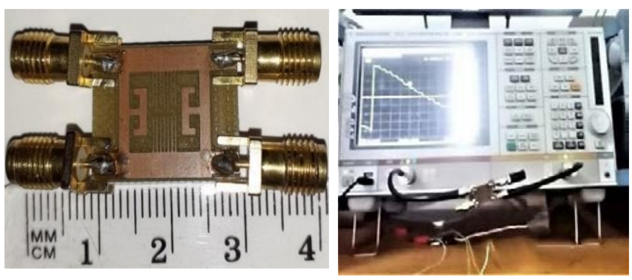


Fig. 8. Proposed branch-line coupler photograph

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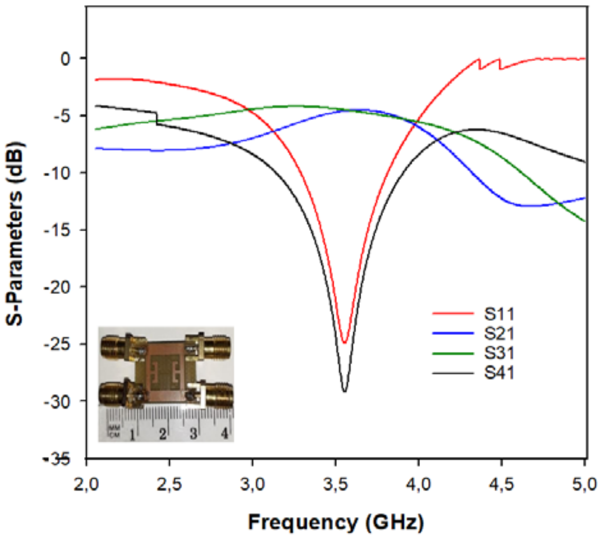

Fig.9. Frequency response of the manufactured LBC

4 Result and discussion

This section, we examine the comparison between the traditional BLC and the design using the T-shape and open stubs. Table 3 illustrates the results of this comparison and demonstrates that this geometry offers a significant reduction in the proposed design size by 52.56% over the conventional one. Meanwhile, the proposed structure return loss and isolation are improved over the conventional one and the amplitude and phase differences between the $S_{21}$and S_{31}parameters are within ±0.1 dB and 90 ±1°, respectively.
Figures 10 and 11 illustrate the strong match of simulated and measured performances of the proposed BLC and demonstrate this structure's success in operating around the desired frequency while maintaining high performance.

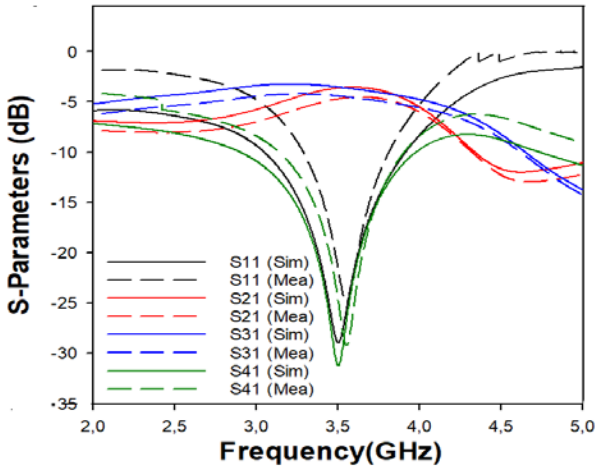

Fig.10. Simulation and measurement results of proposed BLC

To properly evaluate the proposed coupler's performance. A comparison between the BLC proposed in this work and some previously mentioned couplers in terms of frequency responses, phase shift and size are presented in table 4.

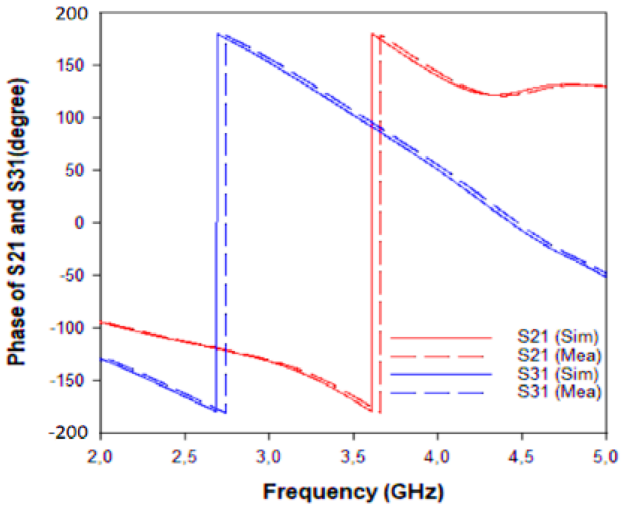

Fig.11. Simulation and measurement phase of the proposed BLC

From this comparison. We can notice that the proposed coupler performance is comparable to other works, although the proposed design implements a simple technique, less complex structure with high quality performance and compact size.

Table 3. Comparison between conventional and proposed BLC

Parameters	Conventional Result	Simulation Result	Measurement Result
Frequency (GHz)	3.5	3.5	3,56
$S_{11}(dB)$	-20	-28.9	-25
$S_{21}(dB)$	-3.8	-3.6	-3.8
$S_{31}(dB)$	-3.7	-3.5	-4.1
$S_{41}(dB)$	-26.1	-31.1	-29.28
Phase Difference (°)	88.97	89	87.9
Area (mm^2)	32×20	19.6×15.5	19.6×15.5
Bandwidth (%)	30	25.05	14.4
Percent reduction (%)		52.56	

Table 4. Performance comparison of the proposed BLC with previously presented designs in the literature.

Ref	Freq. (GHz)	$S_{11}(dB)$	$S_{21}(dB)$	$S_{31}(dB)$	$S_{41}(dB)$	D.P(°)	Size (mm^2)
[1]	3.5	30.69	-2.97	-3.65	-29.28	90	27.2 ×16.5
[11]	3	-21	-(2.3/3.7)	-2.4/4.2	-29	97	25.5 ×16.2
	3	-14	-(2.3/3.7)	-2.4/4.2	-20	98	31 ×16.2
[21]	3.5	-16.31	-3.59	-3.68	-18.37	91.1	20.2 ×23.1
[23]	3	-17	-3.05	-3.16	-34	89.58	23.5 ×16.5
This work	3.5(S)	-28.91	-3.61	-3.52	-31.17	89	19.6×15.5
	3.56 (M)	-25	-3.8	-4.1	-29.28	87.9	19.6×15.5

5 Conclusion

A miniature hybrid branch-line coupler that uses a T-shape and open stubs has been represented. The empty spaces between the quarter-wavelength lines are used to minimize the coupler size by 52.56% compared to conventional designs. The proposed hybrid BLC is simulated at 3.5GHz using the CST studio software, and is engraved on the FR-4 substrate. The scattering parameters and phase difference results of the output ports show a good response. The strong correspondence of measurement and simulation results indicates that this prototype coupler is suitable for 5G applications. In addition, this method is suitable for microwave ICs that require small size.

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