Progress In Electromagnetics Research C, Vol. 82, 199–207, 2018

Miniaturization of Three-Section Branch-Line Coupler Using Diamond-Series Stubs Microstrip Line

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Abstract—A three-section branch-line coupler is miniaturized using diamond-series stubs microstrip lines. The modified coupler is capable of operating from 1.6 GHz to 3 GHz with a return loss of less than −20 dB, phase imbalance of less than 2.5°, insertion loss and coupling of −4.5±1.5 dB and −2.5±0.5 dB, respectively over the operating range. The bandwidth of the coupler has been extended up to 1.4 GHz. In addition, it achieves up to 83.3% size reduction as compared to the conventional three-section coupler. Furthermore, its performance and circuit size are compared with another modified coupler with normal open-stubs microstrip lines. Significantly, this study focuses on analyzing and discussing the effects of diamond structure and number of stubs. Furthermore, the achieved results are superior to the previous studies.

1. INTRODUCTION

Branch-line couplers (BLC) are passive microwave devices primarily used in signal monitoring, power division, and power measurement. The drawback of a conventional branch-line coupler is that at low frequencies it will consume a significant amount of circuit area and provides a narrow fractional bandwidth of 10 to 20% [1]. Even though cascading branch sections can increase the bandwidth of the coupler, it leads to a larger size [2]. On the contrary, for portable RF instruments, a small size coupler is required since the space to install hybrid coupler is limited, and close proximity of RF components is unavoidable [1]. Therefore, several design techniques have been reported for bandwidth enhancement and size reduction of BLCs [3–7]. In [3], asymmetrical T-shaped transmission lines were replaced with regular microstrip transmission lines to reduce the coupler size, which obtained a size reduction of 55%. In [4], the regular microstrip lines of BLC were replaced using lumped circuit elements that are made up of two open stubs separated by a series transmission line. Liao et al. [3] showed that the size of the coupler was reduced by 55.2% with a fractional bandwidth of 56%. Besides lumped circuit elements method, fractal geometry [5] was used to minimize the size of a three-section wideband coupler; the coupler occupied only 27.3% of the conventional BLC size. In [6], the quarter wavelength low impedance arm of conventional BLC was replaced by a compact unit consisting of three unequal open stubs whose slow-wave effect can minimize the coupler area by 70.7% with a fractional bandwidth more than 50%. According to [7], photonic band gap and defected ground structure for the design of BLC can miniaturize the circuit significantly and enhance the bandwidth. However, more sections of hybrids mean a greater size of the coupler. With the recent variety of small sized microwave components, there is a necessity to reduce the coupler size and maintain the bandwidth.

A small, single-layered printed circuit board of a branch line coupler is necessary for portable RF instruments as there is limited space to install the coupler, and close proximity of RF components is unavoidable as mentioned above. A conventional size of coupler can be reduced by defected ground

Received 4 November 2017, Accepted 15 February 2018, Scheduled 3 April 2018
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structure [8], meander lines [9], slow-wave microstrip line structure, as well as stepped impedance resonator [10]. However, majority of modification studies only focused on one-section and two-section branch line couplers [11–17].

This paper proposes a compact and wideband three-section branch-line coupler using slow-wave structure (SWS), meandering line structures (MLS), and diamond-series stubs in the microstrip line in order to improve the operating bandwidth and reduce the size of the couplers. The SWS on the transmission line has the ability to increase the inductance value, L, or the capacitance value, C, of the transmission line which leads to a reduced phase velocity, v, of the signal transfer across the transmission line. Moreover, the continuous folding of the transmission line MLS helps to minimize the resonant length.

From this study, it is found that the diamond-series stubs structure is more efficient than the open stubs structure in shifting the operating frequency from higher value to lower value while maintaining the shorter length of the branch lines. It is the first time that the series diamond stubs are utilized as impedance match element in the branch-line coupler design. It is worth to mention that when using the proposed seven-series diamond stubs, both the overall coupler length and stub size are reduced compared to that of the design mentioned in Section 3. In addition, by adjusting the dimensions of the diamond stubs, the operating bandwidth can be wider than that of the coupler with the open stubs.

2. TRANSMISSION LINE LENGTH REDUCTION

In this section, three kinds of microstrip transmission lines are compared in terms of the length at center frequency, f of 2.4 GHz. Figure 1(a) shows a regular microstrip line with a total length, L, of 47 mm while Figure 1(b) depicts a modified microstrip line with four open stubs with a total length of 22 mm, which is reduced by 53.2% compared to a regular line. In addition, Figure 1(c) shows another modified microstrip line using three diamond-series stubs with a total length, L, of 16.3 mm, which successfully achieves a length reduction of 65.3% compared to the regular microstrip line in Figure 1(a).

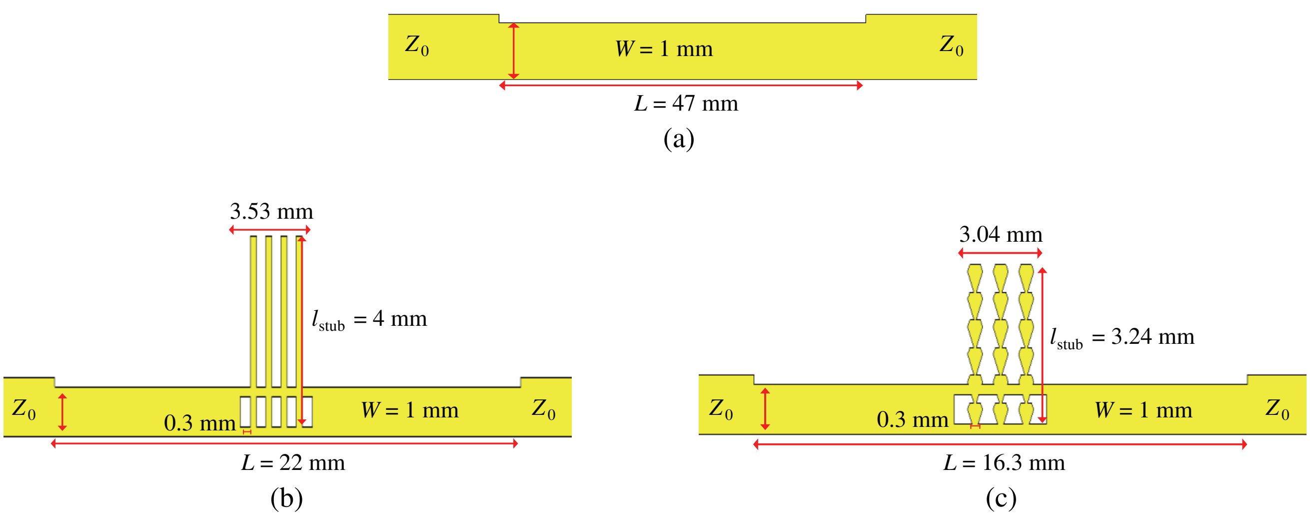


Figure 1. (a) Regular transmission line, (b) modified transmission line using open-stub, (c) modified transmission line using diamond-series stub.

Figures 2(a) and (b) demonstrate the return loss, $|S_{11}|$, and insertion loss, $|S_{21}|$, of the three transmission lines versus operating frequency from DC to 5 GHz. From Figure 2, it is noticed that $|S_{11}|$ and $|S_{21}|$ of the modified microstrip line with diamond-series stubs give a better performance (lowest value of $|S_{11}|$ and highest value of $|S_{21}|$) than other two microstrip lines. Moreover, Figures 3(a) and (b) depict the real and imaginary parts of the input impedance, Z_{in}, obtained from complex S_{11} as:

$$Z_{in} = Z_o \frac{1 + S_{11}}{1 - S_{11}} = \Re\left(Z_{in}\right) + j\Im\left(Z_{in}\right) \tag{1}$$

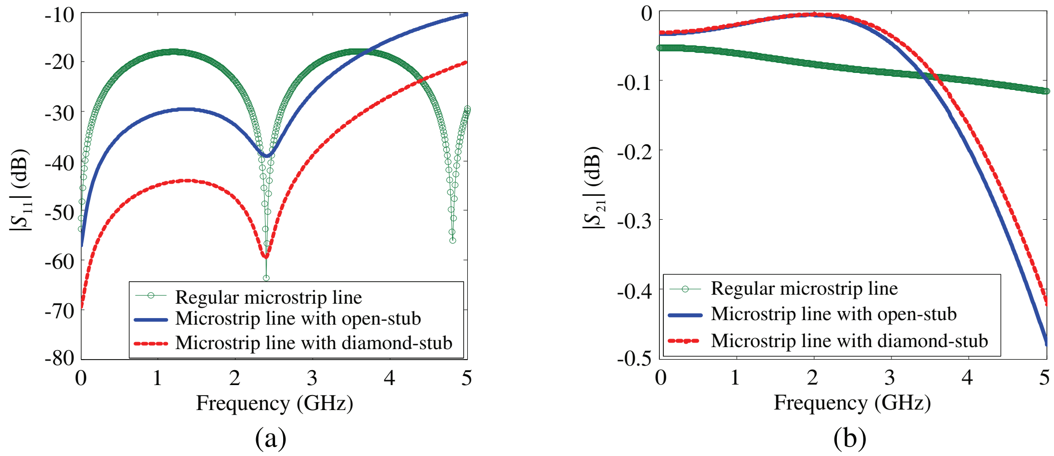


Figure 2. (a) Return loss $|S_{11}|$, and (b) insertion loss $|S_{21}|$.

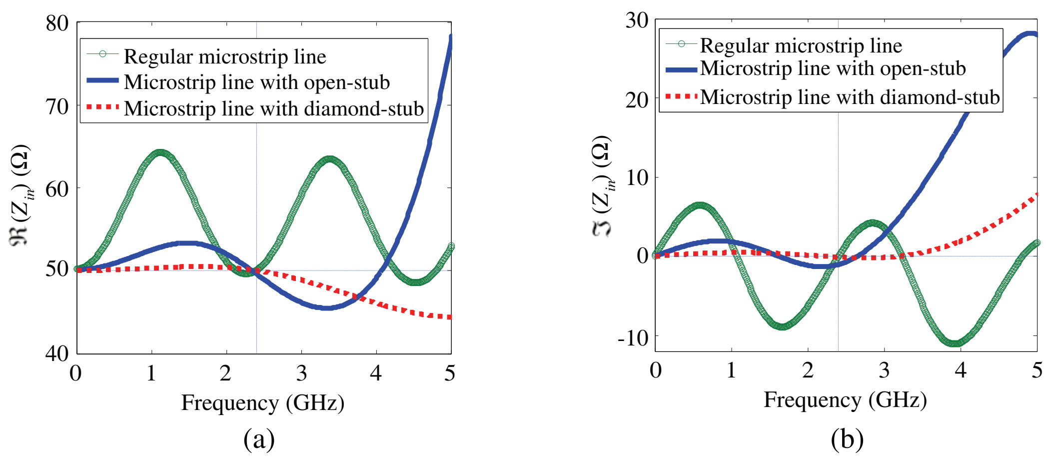


Figure 3. (a) Real and (b) imaginary parts of the input impedance, Z_{in} for the three transmission lines.

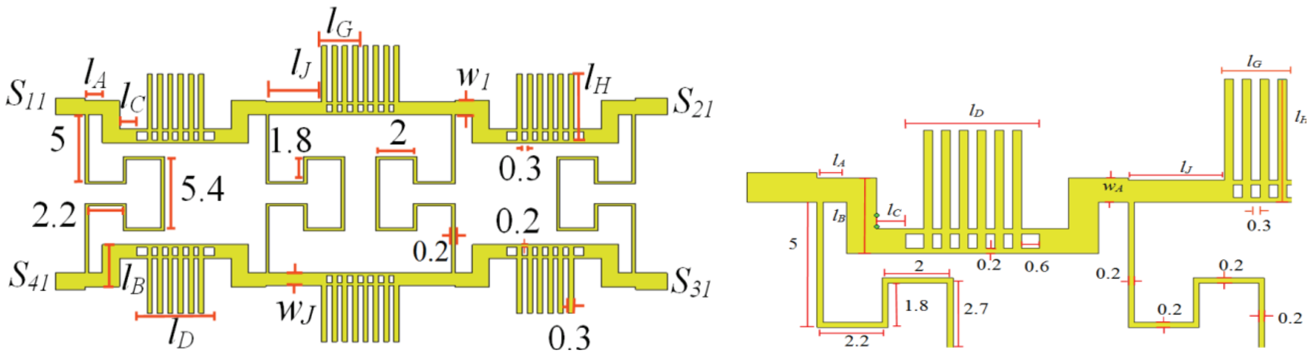
Table 1. Comparison between the regular and modified transmission lines.

Specification	Microstrip line at 2.4 GHz		
	Regular	**Open-Stub**	**Diamond-Series Stub**
Length, L (mm)	47	22	16.3
Length reduction (%)	-	53.2	65.3
Num. of stubs, N_{stub}	-	4	3
Stub length, l_{stub} (mm)	-	4	3.24
$\Re\text{e}(Z_{in})$ (Ω)	50	49.62	49.97
$\Im\text{m}(Z_{in})$ (Ω)	0.5	−1.05	−0.17

From Figure 3(a), it can be noted that $\Re(Z_{in})$ of the microstrip line with diamond-series stubs is close to 50 Ω from DC to 3 GHz and $\Im(Z_{in})$ closed 0 Ω from DC to 4 GHz. This gives a good bandwidth compared to the regular line and the line with open stubs. $\Re(Z_{in})$ of the microstrip lines with open stubs and diamond-series stubs are 49.62 Ω and 49.97 Ω, respectively at $f = 2.4$ GHz. Clearly the shorter microstrip line can be achieved by using three of seven-series diamond stub. Table 1 shows the comparison between modified transmission lines and regular one.

3. BRANCH-LINE COUPLER WITH NORMAL SERIES OPEN STUBS STRUCTURE

Figure 4 shows the modified three-section coupler using SWS, MLS, and open stubs. The dimensions are given in millimeter unit and tabulated in Table 2.



(a) (b)

Figure 4. (a) The first modified three-section coupler. (b) Quarter circuit of the modified coupler.

Table 2. List of dimensions of the modified branch-line coupler with normal open stubs.

Dimensions			
Symbols	**Values (mm)**	**Symbols**	**Values (mm)**
l_A	1.0	W_A	1.0
l_B	3.0	W_J	0.9
l_C	1.0	l_G	2.25
l_D	4.5	l_H	5.0
l_J	3.25		

The compact and wideband three-section branch-line coupler is modified based on [20] by adjusting the number of open stubs in each horizontal branch line section and folding the line sections. This will improve the operating bandwidth and reduce the size of couplers to 85% compared to the conventional three branch line coupler. The first and third horizontal branches have six open-stubs while the middle section has eight open stubs. The design procedures of the three-section coupler is demonstrated in four steps:

Step 1

The dimension of the three-section branch-line coupler is designed using an RT/Duroid 5880 substrate ($\varepsilon_r = 2.2$, $\tan\delta = 0.001$ and thickness $h = 0.38$ mm) based on the given characteristic impedance, $Z_o = 50\,\Omega$, $Z_1 = 140\,\Omega$, $Z_2 = 54\,\Omega$, $Z_3 = 58.3\,\Omega$ and $\theta_1 = \theta_2 = \theta_3 = 90^\circ$ in [2] and [4]. From the above given parameters, the corresponding length, l, and width, W, of the branch lines of the coupler are estimated using TX-Line program calculator.

Step 2

The initial designed circuit structure is simulated using Computer Simulation Technology (CST). The performance of the coupler is observed based on the simulated S-parameters (return loss $|S_{11}|$, insertion loss $|S_{21}|$ & $|S_{31}|$, and isolation $|S_{41}|$).

Step 3

The initial circuit structure is miniaturized by bending the vertical (shunt) microstrip branch line into a loop line form.

Step 4

The circuit structure is further miniaturized by adding a slow-wave structure, which is a series of open-stub on the horizontal branch line to achieve the desired size. The total size reduction is 83.3% compared to the size of a conventional coupler. The performance of the coupler is optimized by minor adjustment of the length, width, and distance gap between the open stubs as well as the number of open stubs on the horizontal branch line.

Finally, the designed circuit structure is printed on an RT/Duroid 5880 substrate and tested using Keysight E5071C network analyzer.

4. BRANCH-LINE COUPLER WITH DIAMOND-SERIES STUBS

Figure 5 shows the modified three-section branch-line coupler with diamond-series stub. The same previous design in Section 3 is used with the exception that the open-stubs are replaced by seven-series diamond stubs. This is done to show the superior effects of using series diamond stubs in terms of bandwidth and size.

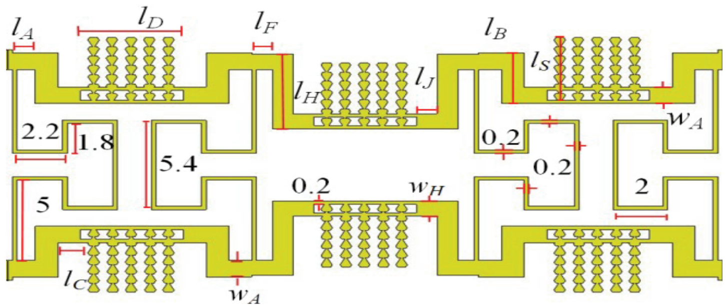


Figure 5. The second modified four branch line coupler.

In Figure 6(b), the diamond-series stubs are modified based on a single diamond open-stub [18]. Taking into account the single diamond-stub, one can divide it into n discrete segments of microstrip transmission line of length δ. Length δ needs to obey the condition $\delta \ll \lambda_g$, where λ_g is the electrical wavelength. The narrow width segment of the stub having higher characteristic impedance is merged with the microstrip transmission line of the coupler. Figure 6(a) shows the last wide segment of the stub with low impedance which acts as open-ended discontinuity.

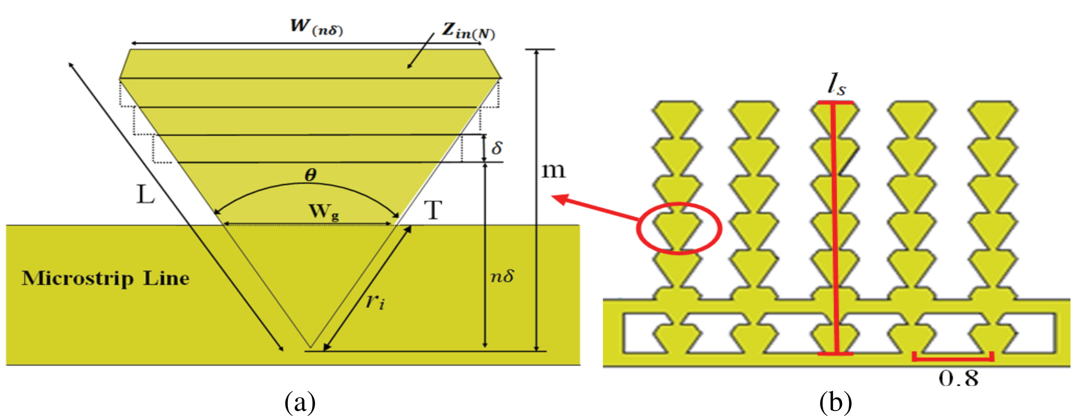


Figure 6. (a) Geometry of the single diamond stub [18]. (b) Seven-series diamond stubs.

According to [15], the transmission line widths, $W_{n\delta}$, of the segments are obtained by:

$$W_g = 2r_i \sin(\theta/2) \tag{2}$$

$$W_{n\delta} = (2n\delta) \times \tan(\theta/2) \quad n = 0, 1, \ldots, N \tag{3}$$

The input impedance, $Z_{in(n)}$, of each n-segments is obtained by Equation (4) with an exception of the final section ($Z_{in(N)}$) since it has open-ended discontinuity. When $W_{n\delta}/h > 1$, the input impedance, $Z_{in(n)}$, of each n-segments is calculated as in [1]:

$$Z_{in(n+1)} = Z_{in(n)} \frac{Z_{o(n)} + jZ_{in(n)} \tan(\beta\delta)}{Z_{in(n)} + jZ_{o(n)} \tan(\beta\delta)} \quad (4)$$

where β is the wave number, and the characteristic impedance, $Z_{o(n)}$, of each n-segment is expressed as:

$$Z_{o(n)} = \frac{120\pi}{\sqrt{\varepsilon_{eff}}\,\{(W_{n\delta}/h) + 1.393 + 0.667 \ln\left[(W_{n\delta}/h) + 1.444\right]\}} \quad (5)$$

The input impedance of the diamond-stub can be found from the computation of the input impedance, $Z_{in(n)}$, of each cascaded transmission line with incremental distance δ. According to Equations (2) to (5), n is chosen to be 19. The electrical parameters for the diamond-stub are computed as $W_g = 0.09$ mm, $L = 1.88$ mm, $r_i = 0.5$ mm, $\theta = 10°$, $W_{n\delta} = 0.33$ mm, and $\delta = 0.01$ mm. The designed coupler dimensions in Figure 5 using seven-series diamond-stubs are tabulated in Table 3.

Different series of diamond-stubs are simulated in order to get the desired performance at 2.4 GHz as shown in Figure 7. Clearly, it can be noted that the desired performance is obtained when using five stubs with seven series for each stub. The length of this seven-series diamond stub, l_s, is 3.4 mm which is smaller than that of the regular open-stub structure, l_H, in Section 3.

Table 3. Values of the second design parameters.

Dimensions			
Symbols	Values (mm)	Symbols	Values (mm)
l_A	1.0	l_G	2.25
l_B	3.0	l_H	4.5
l_C	1.0	l_J	0.9
l_D	4.5	w_A	1.0
L_F	0.9	w_h	0.2

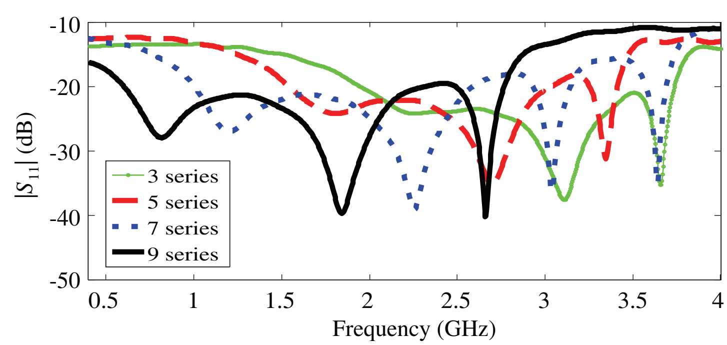


Figure 7. Different series of diamond-stubs.

5. RESULTS AND DISCUSSION

Figures 8 and 9 show the simulated and measured S-parameters results of the modified three-section coupler for comparison purpose. Clearly, the modified coupler using the diamond-series stubs is capable of enhancing the operating bandwidth compared with the coupler using the open stubs. From Figure 9(a), it can be noted that the measurement value of $|S_{11}|$ is below -15 dB from 1.57 GHz to

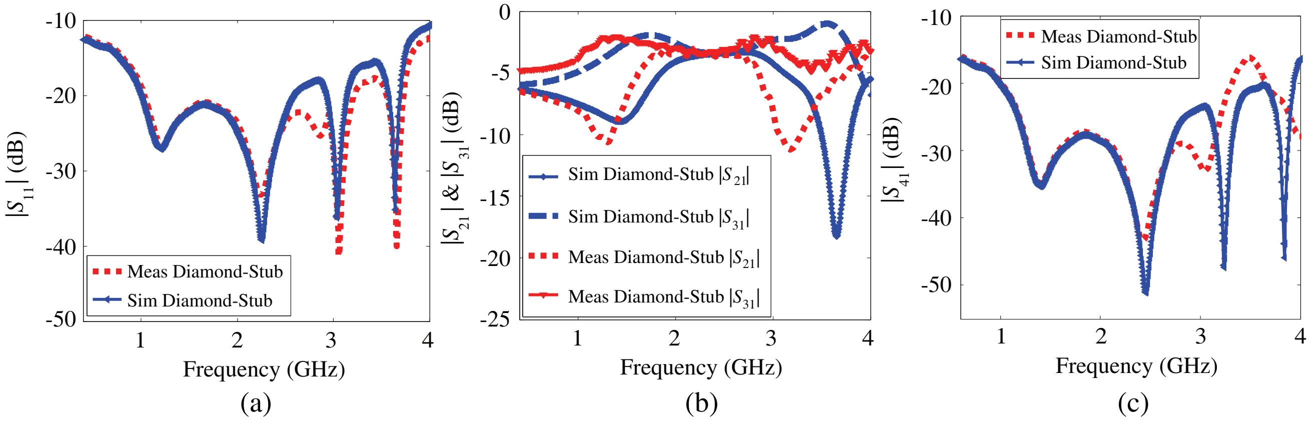


Figure 8. Simulations and measurements results of modified couplers using series diamond-stub, (a) return loss, $|S_{11}|$, (b) insertion loss, $|S_{21}|$ & coupling $|S_{31}|$, (c) isolation, $|S_{41}|$.

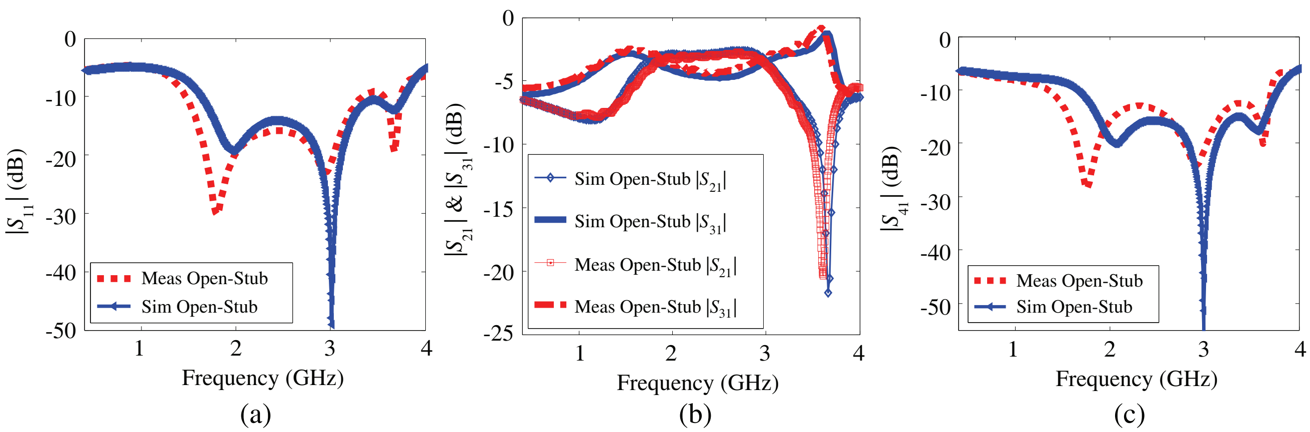


Figure 9. Simulations and measurements results of modified couplers using open-stub, (a) return loss, $|S_{11}|$, (b) insertion loss, $|S_{21}|$ & coupling $|S_{31}|$, (c) isolation, $|S_{41}|$.

3.1 GHz for the modified coupler using the open stubs while it is below -20 dB from 1 GHz to 3.2 GHz for the modified coupler using the diamond-series stubs in Figure 8(a). In Figure 9(c), $|S_{41}|$ is below -13 dB from 1.52 GHz to 3.5 GHz for the modified coupler using the open stubs while it is -20 dB from 1 GHz to 3.14 GHz for the one with the diamond-series stubs in Figure 8(c). As shown in Figure 9(b), the insertion loss and coupling, $|S_{21}|$ & $|S_{31}|$ for the coupler using the open stubs, are -2.75 dB to -6 dB and -2.6 dB to -4.6 dB from 1.5 GHz to 3.2 GHz, respectively. Figure 8(b) shows the insertion loss and coupling, $|S_{21}|$ & $|S_{31}|$ for coupler using the diamond-series stubs, and their values are -3 dB to -6 dB from 1.5 GHz to 3.1 GHz and -2.05 dB to -4 dB from 1.4 GHz to 3.2 GHz, respectively. The directivity of the modified coupler using diamond-series stubs is below -20 dB and below -10 dB for the coupler using open stubs as depicted in Figure 10. The measured phase differences, $\angle|S_{21}| - \angle|S_{31}|$ for the modified coupler using the open stubs and the coupler using a seven-series diamond stub, are $85.7^\circ \pm 3.3\circ$ and $94.7 \circ \pm 2.5\circ$, respectively, over the operating bandwidth 1.6 GHz to 3 GHz as shown in Figure 10(b).

Figure 11 shows the circuit photograph of the proposed branch coupler using the open stubs with an overall size of 31 mm $\times$ 17 mm and the circuit photograph using the seven-series diamond stubs which has a circuit size of 30 mm $\times$ 15.2 mm. Therefore, the modified couplers have achieved size reductions of 80.8% and 83.3%, respectively, compared to the conventional three branch line coupler [20]. From the results, it is obvious that the modified coupler using the seven-series diamond stubs is capable of enhancing the operating bandwidth and reducing the size. Table 4 proves that the results achieved by this study are superior to the previous studies.

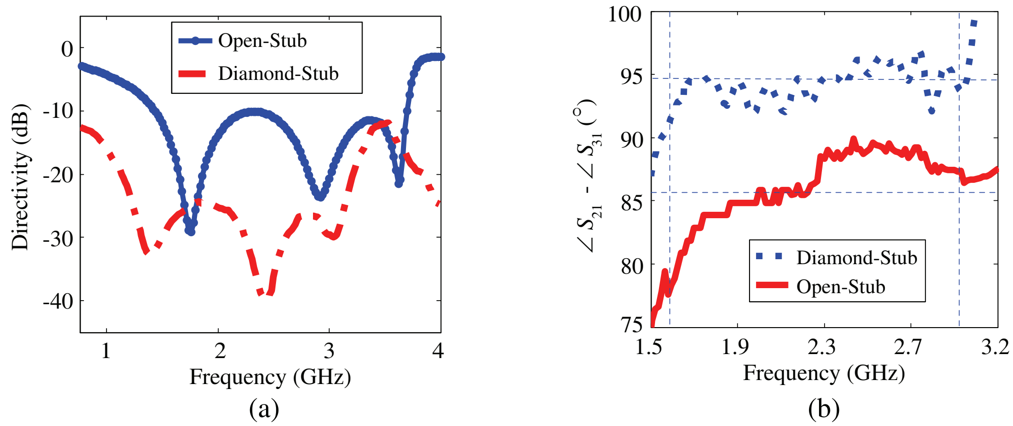


Figure 10. (a) Directivity and (b) $\angle S_{21} - \angle S_{31}$ of modified couplers.

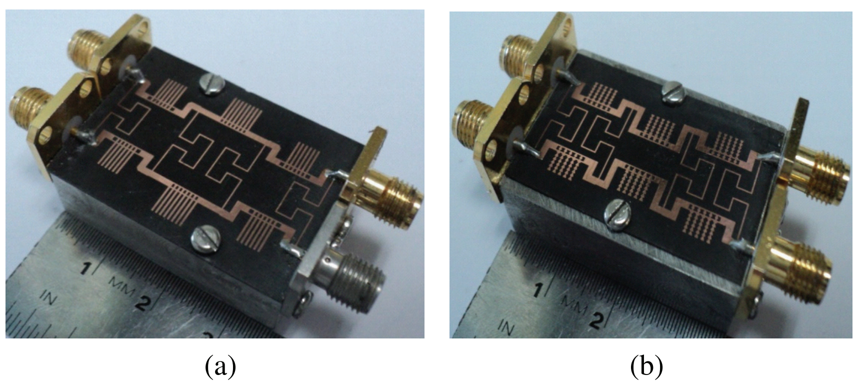


Figure 11. Circuits photograph, (a) BLC with normal open-stub and (b) BLC with diamond-series stubs.

Table 4. Comparison performance of various couplers.

Ref	**Center Freq (GHz)**	**FBW (%)**	$\lvert S_{11} \rvert$ **(dB)**	**Size area (mm²)**
[5]	2	61.5	−15	$0.065\lambda_g^2$
[6]	1.1	55.67	−15	$0.07\lambda_g^2$
[7]	2.1	47.61	−20	$0.144\lambda_g^2$
[19]	2	45	−15	$0.07\lambda_g^2$
[20]	2.4	77	−14	$0.16\lambda_g^2$
Conventional	2.4	62.5	−15	$0.32\lambda_g^2$
This study:				
BLC with normal open-stub	2.4	72	−15	$0.07\lambda_g^2$
BLC with diamond-series stubs	2.4	83.33	−20	$0.06\lambda_g^2$

6. CONCLUSION

A methodology for the design of the three-section branch-line coupler using a slow-wave structure, meandering line and series-diamond subs has been successfully applied to the branch-line coupler for bandwidth extension and miniaturization purpose. The performances of the modified coupler are acceptable with good agreement at the center frequency of 2.4 GHz and fractional bandwidth of 83.33% from 1.5 GHz to 3.1 GHz. A shorter branch line coupler with smaller stub and more enhancement of the bandwidth have been achieved too. Compared with open stub, series diamond stub is superior to get a significant improvement in terms of performance and size reduction.

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