A Design of Branch-Line Coupler with Harmonic Suppression and Size Reduction Using Closed-Loop and Open-Loop Resonators

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Abstract. *In this paper, a branch-line coupler using closed-loop and open-loop resonators with the operating frequency of 2.69 GHz is proposed. The designed microstrip circuit not only is able to suppress the second and the third unwanted harmonics but also reduces the occupied area to 59% of the traditional branch-line coupler. To explain how the employed resonators can suppress spurious frequencies, transmission zeros of both resonators based on their equivalent LC has been calculated, separately. To prove the abilities of the proposed branch-line coupler, the designed circuit has been fabricated and tested resulting in a good agreement between the measurement and simulation results. According to the S_{11} when it is less than –15 dB the bandwidth of the designed branch-line coupler is about 500 MHz, from 2.42 to 2.92 GHz .The comparison between the results of simulation and measurement are in good agreement.*

Keywords

Harmonic suppression, microstrip circuit, miniaturized branch-line coupler

1. Introduction

Branch-line couplers as an equal/unequal power splitter are one of the key blocks in microwave applications such as balanced amplifiers, data modulators and butler matrix. The traditional branch-line coupler is composed of four quarter-wave length transmission lines which the front transmission lines have the same characteristic impedance of Z_o and $Z_o/\sqrt{2}$ [1]. The used quarter-wave length transmission lines increase the occupied area and subsequently the chip cost enhances in the monolithic microwave integrated circuits (MMICs), especially it appears more at lower frequencies. Furthermore, the conventional branch-line coupler is not capable of suppressing spurious frequencies. In order to overcome these defects, various methods have been reported in [2–10] so far. In [2], a slow-wave branch-line coupler using high-low impedance resonators is designed. Utilizing these kinds of resonators reduces the circuit size to 28% of the conventional branch-line coupler at 2 GHz and suppresses the second harmonic, too. Two different equivalent circuits of quarter-wave length transmission line with T-shaped structure and dual transmission line are applied to the branch-line couplers, in [3] and [4]. Using equivalent T-shaped lines in the structure of the branch-line couplers has reduced the overall surface to 45% and 63.9% of the conventional coupler in [3] and [4], respectively. However, these methods are not capable of harmonic suppression and they both can only operate around a single frequency of 2 GHz. Another method to introduce a branch-line coupler with almost 60% size reduction is manipulating the reactive characteristics of discontinuities in its microstrip lines [5], but the proposed structure is failed in suppressing unwanted harmonics. Interdigitated shunt capacitances are placed inside the branch-line coupler, in [6]. The use of shunt capacitor not only can suppress second harmonic about 20 dB but also leads to an acceptable miniaturization in comparison to the conventional branch-line coupler. In [7], by serving a microstrip electromagnetic bandgap (EBG) element entitled MEBE a miniaturized branch-line coupler has been designed. In this case, better than 30 dB suppression for the second harmonic and 18 dB suppression for the third harmonic are obtained. The same properties as EBG can be achieved by utilizing defected ground structure (DGS) in the structure of a branch-line coupler, as it is reported in [8]. Unfortunately, EBG and DGS need etching process at both sides and they cannot be utilized on metal surface. A compact microstrip rat-race hybrid employing space-filling curves is reported in [9], and the proposed circuit occupies 31% of the area of the conventional design. However, the employed curves have not suppressed any spurious frequencies. In [10], to reduce the physical size of the branch-line coupler, the distributed capacitors are placed within the empty space of the coupler and about 62% size reduction is achieved, but the proposed structure is failed in harmonic suppression. In [11], a branch-line coupler was presented by periodically loading open end stubs with the coupler, although, the size reduction of this circuit is only 37% in analogy with the conventional case. In this paper, to suppress spurious frequencies and reduce the occupied area both open-loop and closed-loop resonators are employed inside the free area of the traditional branch-line coupler.

2. The Procedure of Designing

Figures 1a and b show the conventional branch-line coupler and its equivalent LC circuit at operating frequency of 2.69 GHz, respectively. The values of calculated inductors and capacitors of the shown LC circuit in Fig. 1b are as follows [1]: $L_{1conventional}$ = 2.01 nH, $L_{2conventional}$ = 2.97 nH, $C_{1conventional}$ = 1.68 pF, $C_{2conventional}$ = 1.187 pF. In Fig. 1c and d, the frequency responses of the traditional branch-line coupler and its equivalent LC circuit at operating frequency of 2.69 GHz are shown, respectively. The configuration of the proposed branch-line coupler with operating frequency of 2.69 GHz has been shown in Fig. 2, which is composed of open-loop and closed-loop resonators. The used resonance cells are mounted inside the free area of the conventional branch-line coupler as the procedure will be explained in the following lines. In the first step, a conventional branch-line coupler with an operating frequency of 2.69 GHz is designed as it is shown in Fig. 1a. In order to increase the capacitor and inductor loadings on each $\lambda/4$ transmission line (TLIN), two different resonators with the primary dimensions of $A = B = 0.1$ mm, $C = D = 0.1$ mm are added inside the free area of the conventional case. These values are selected to control the effects of changing dimensions on frequency response and determining the operating frequency. The locations of the added resonators are determined with *a, b, c* and *d* in Fig. 2. By increasing the values of *A, B, C* and *D*, both capacitor and inductor loading can be obtained. In order to reduce the occupied area of the branch-line coupler, the length of the main TLIN can decrease simultaneously, with increasing the dimensions of open-loop and close-loop patches. Note that changing the values of variables does not have to shift the desired operating frequency, i.e. 2.69 GHz. To have more degree of freedom, the open-loop and close-loop patches employing TLINs with different dimensions, i.e. $A \neq B$ and $C \neq D$ have been utilized. Based on the characteristic of the lowpass resonators in their frequency response, which is the stopband effect generated by enhancing distributed inductance and capacitance, these resonators can be useful to suppress high order harmonics and size reduction in branch-line couplers [1]. Figure 3a illustrates the configuration of the first resonator. As it is shown, resonator 1 is consisted of an open-loop patch with two open-stubs. Thus, the equivalent LC circuit of this resonator has two capacitances, which are modeled by C_{r1} and C_{r3} (see Fig. 3b). L_{r3} and L_{r4} model the thin transmission line of two open-stubs. L_{r1} and L_{r2} account for the transmission lines determined by 1.4 mm and 7.75 mm lengths in Fig. 3a, respectively. C_{p1}, C_{p2}, C_{p3}, C_{r2} present the capacitance between the microstrip structure and the ground.

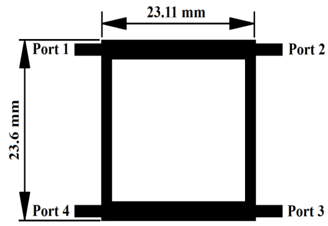

Fig. 1a. The topology of the conventional branch-line coupler at operating frequency of 2.69 GHz.

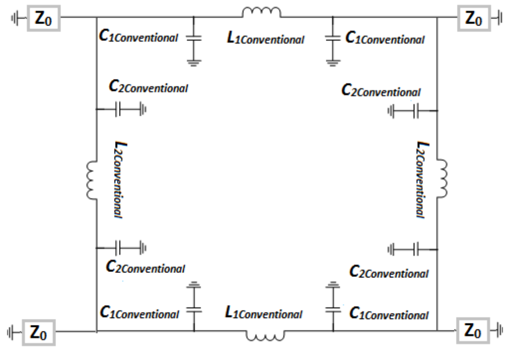

Fig. 1b. The equivalent LC circuit of conventional branch-line coupler at operating frequency of 2.69 GHz.

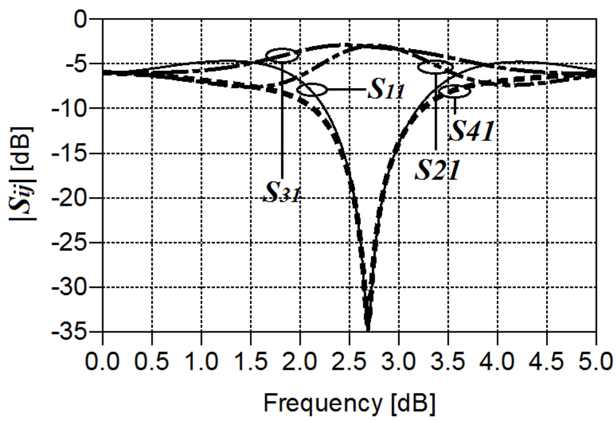

Fig. 1c. The EM-simulation results of the traditional branch-line coupler at 2.69 GHz (|S11|, |S41|, |S21| and |S31|).

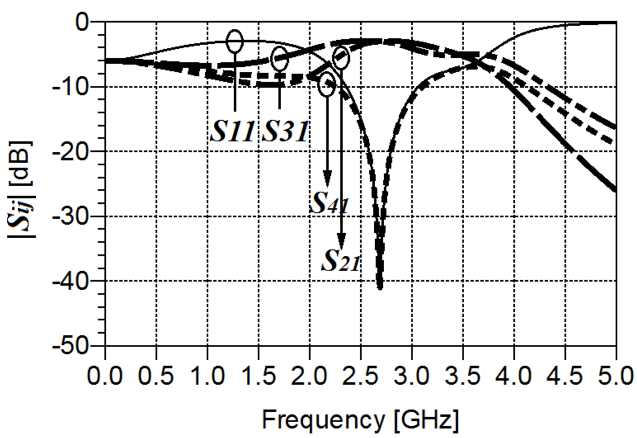

Fig. 1d. Performance of the equivalent LC circuit of the conventional branch-line coupler at 2.69, (|S11|, |S41|, |S21| and |S31|).

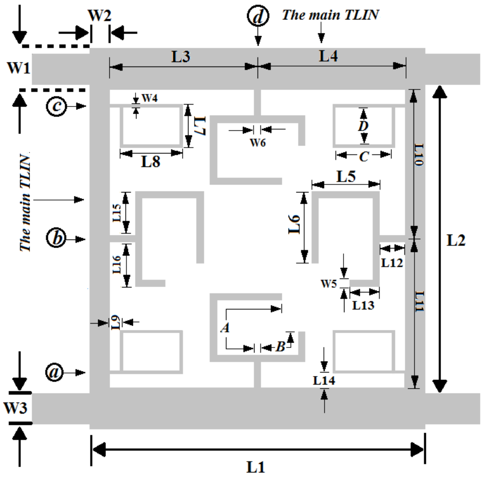

Fig. 2. The topology of the proposed branch-line coupler at 2.69 GHz.

The frequency response of resonator 1 and its equivalent LC circuit are shown in Fig. 3c. The calculated values of LC circuit of resonator 1 are shown in Tab. 2 [1]. Resonator 2 is composed of a square microstrip closed-loop patch, as it is shown in Fig. 4a. The equivalent LC circuit of this resonator is depicted in Fig. 4b. In the equivalent lumped circuit of this resonance cell, $L1$ and $L2$ account for high impedance lines of closed-loop patch. $L4$ models the transmission line determined by 0.6 mm length in Fig. 4a [1]. $L3$ and $L4$ determine the equivalent inductors of the main transmission line of this resonator. $C0$, $C1$, $C2$ and $C3$ present the created capacitances between the microstrip structure and the ground. Fig. 4c shows the frequency responses of resonator 2 and its equivalent LC circuit. The calculated values of the equivalent LC circuit of resonator 2 are shown in Tab. 2 [1]. The values of lumped elements of the designed resonators has been obtained on (RT/Duroid 5880), a substrate with a relative dielectric constant $\varepsilon_r = 2.2$, thickness $h = 0.508$ mm and loss tangent $\tan\delta = 0.0009$. According to the frequency responses of the designed resonators, i.e. resonators 1 and 2, they can suppress spurious frequencies at 5.5 GHz and 9.19 GHz, respectively. Therefore, employing resonator 1 and 2 in the structure of the proposed coupler leads to suppressing second and third harmonics. To clarify the effect of changing the dimensions of microstrip transmission lines of the presented resonators on the frequency response, transition zeros of each resonance cell according to their equivalent LC circuits have been extracted, separately. Thus, to calculate transition zeros based on the lumped circuits of the main resonators, their insertion loss equations have been equaled to zero, separately.

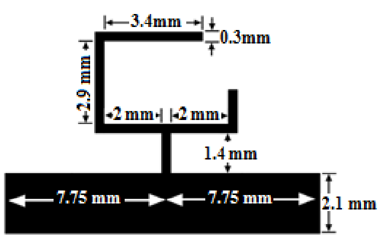

Fig. 3a. The structure of the first resonator.

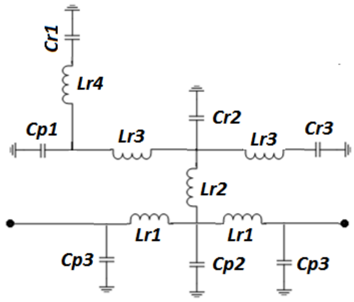

Fig. 3b. The equivalent LC circuit of resonator 1 [1].

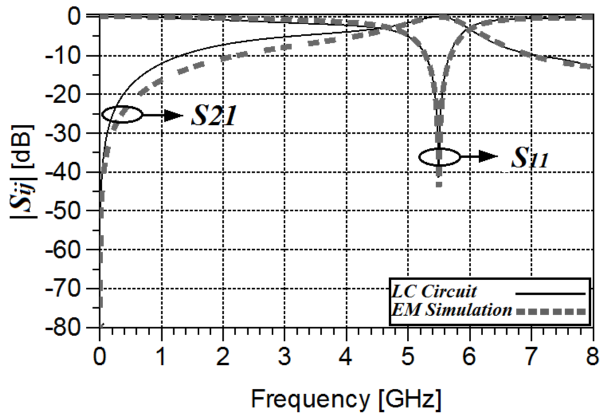

Fig. 3c. The comparison between LC simulation and EM simulation results of resonator 1(|S11| and |S21|).

The transition zeros are given as:

$$f_{z(\text{closed-loop})} = \frac{1}{2\pi}\sqrt{\frac{L_1 + L_2}{L_1 L_2 C_2}}, \tag{1}$$

$$f_{z(\text{open-loop})} = \frac{1}{4\pi}\sqrt{\begin{array}{l}(\frac{1}{C_{p1}L_{r4}} + \frac{1}{C_{r1}L_{r4}} \\ + \frac{1}{C_{p1}L_{r3}} + \frac{1}{C_{r2}L_{r3}} \\ + \frac{1}{C_{r2}L_{r3}} + \frac{1}{C_{r3}L_{r3}} \\ - \frac{1}{C_{r2}L_{r2}})\end{array}} \tag{2}$$

Clearly, by changing the $L1$, $L2$ and $C2$ in the lumped circuit of the closed-loop resonator and C_{p1}, C_{r1}, L_{r4}, L_{r3}, C_{r2}, L_{r2}, L_{r3} and C_{r3} in the LC circuit of the open-loop resonator, their transmission zeros and consequently their suppression ability can be controlled. Instead of the mentioned lumped element, their corresponding microstrip realizations can be utilized to control the spurious frequencies suppression in the branch-line coupler. Note that using these resonators in the structure of the proposed coupler affects their frequencies. On the other hand, the utilized resonators could increase the inductor and capacitance per unit length of the main transmission lines of the proposed coupler in comparison to the conventional branch-line coupler. Thus, the phase velocity decreases and size reduction can be achieved [1].

All in millimeter			
L1=17.5	L7=2.2	L13=1.5	W3=1.55
L2=15.5	L8=3.2	L14=0.8	W4=0.1
L3=7.7	L9=0.6	L15=2.3	W5=0.3
L4=7.7	L10=7.75	L16=2.3	W6=0.3
L5=3.5	L11=7.75	W1=2.1	
L6=3.7	L12=1.4	W2=1	

Tab. 1. The dimensions of the proposed branch-line coupler

The dimensions of the proposed branch-line coupler illustrated in Fig. 2 are shown in Tab. 1.

Figure 5a shows the equivalent LC circuit of the proposed branch-line coupler. A comparison between LC simulation and EM simulation results of the designed branch-line coupler are depicted in Figs. 5b and c. As it can be seen, the frequency responses of the EM simulation and the equivalent LC circuit of the designed coupler are in good agreement around operating frequency of 2.69 GHz. The values of the calculated inductors and capacitances of the illustrated circuit in Fig. 5a are shown in Tab. 3 [1]. Note that to simplify the equivalent lumped circuit of the presented coupler, the LC circuit of resonator 1 has been replaced by only L_{rf} and C_{rf}, as shown in Fig. 5a.

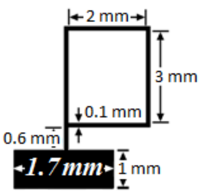

Fig. 4a. The structure of the second resonator.

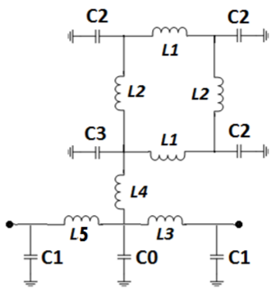

Fig. 4b. The equivalent LC circuit of resonator 2 [1].

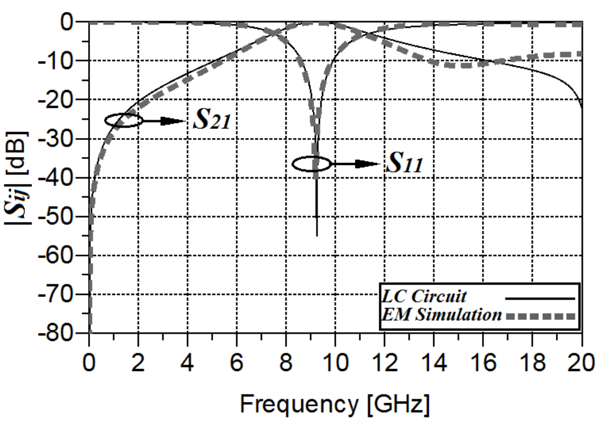

Fig. 4c. The comparison between LC simulation and EM simulation results of resonator 2(|S11| and |S21|).

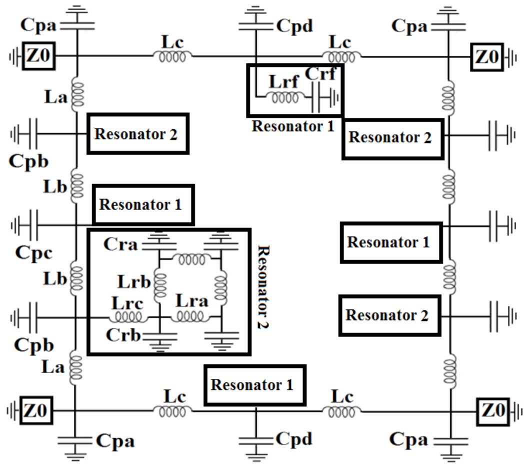

Fig. 5a. The equivalent LC circuit of the proposed branch-line coupler at 2.69 GHz.

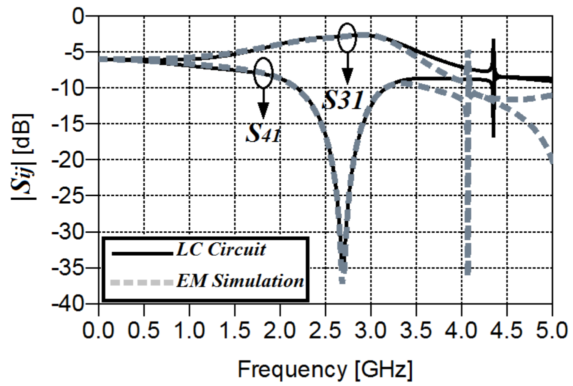

Fig. 5b. The comparison between LC and EM simulations of the proposed coupler (|S41| and |S31|).

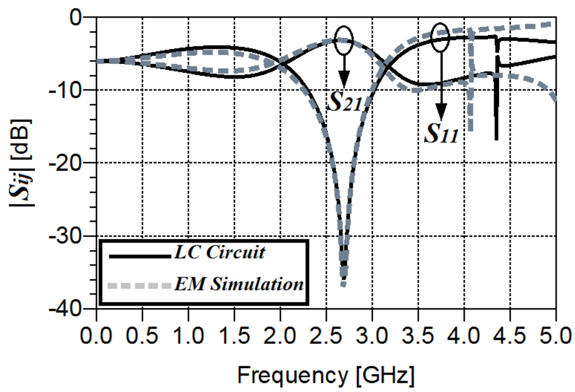

Fig. 5c. The comparison between LC and EM simulations of the proposed coupler (|S11| and |S21|).

Resonator 1		Resonator 2	
Cr1	0.192 pF	L1	1.44nH
Cr2	0.101 pF	L2	2.14nH
Cr3	0.083 pF	L3	1.935nH
Lr1	0.96 nH	L4	0.432nH
Lr2	0.817 nH	L5	1.935nH
Lr3	1.39 nH	C0	0.264pF
Lr4	1.22 nH	C1	0.027pF
Cp1	0.083 pF	C2	65fF
Cp2	1.003 pF	C3	73Ff
Cp3	0.488 pF		

Tab. 2. The values of lumped elements of resonators 1 and 2.

La	0.24 nH	Crb	73 pF
Lb	1.965nH	Lra	0.24 nH
Lc	1.36 nH	Lrb	1.36 nH
Lrf	0.72 nH	Lrc	0.462 nH
Crf	0.471 pF	Cpa	0.5573 pF
Cra	65 fF	Cpb	0.2654 pF
Cpc	0.475 pF	Cra	73 fF
Cpd	0.9 pF	Crb	65 pF

Tab. 3. The values of lumped elements of the proposed coupler shown in Fig. 5a.

3. The Results of Simulation and Measurement

The proposed branch-line coupler has been constructed on RT/Duroid 5880, a substrate with a relative dielectric constant $\varepsilon_r = 2.2$, thickness $h = 0.508$ mm and loss tangent $\tan\delta = 0.0009$. The results of simulation and measurement of S-parameters were carried out on an EM-simulator ADS based on the method of moment and an Agilent network analyzer HP8558, respectively. The frequency responses are shown in Figs. 6 to 10. According to the measurement results the operating frequency of the proposed branch-line coupler is located in 2.69 GHz. The measurements in Fig. 6 and 7 depict that at 2.69 GHz, $|S_{21}| = -3.4$ dB and $|S_{31}| = -3.03$ dB.

Furthermore, the second and third harmonics in the shown $|S_{21}|$ are suppressed better than –14 dB and –25 dB and these harmonics have been suppressed better than –30 dB and –25 dB in the plotted $|S_{31}|$. Note that the conventional branch-line coupler is not capable of harmonic suppression, based on its frequency response shown in Fig. 1c. As it is observed from Fig. 8 and 9, both $|S_{11}|$ and $|S_{41}|$ are about –20 and –27 dB at the operating frequency, respectively. Figure 10 shows the phases of ports 2 and 3, which are about 80.83 degree and –11.97 degree around operating frequency of the coupler. The experimental results indicate that, the measured insertion loss of the proposed circuit has a good agreement with the simulated insertion loss of the conventional branch-line coupler.

The occupied area of the constructed coupler and conventional case are 17.5 mm × 18.5 mm and 23.2 mm × 23.6 mm, respectively. It depicts that, the circuit size of the proposed structure has been reduced to around 59% of the conventional branch-line coupler at operating frequency of 2.69 GHz. This reduction in overall

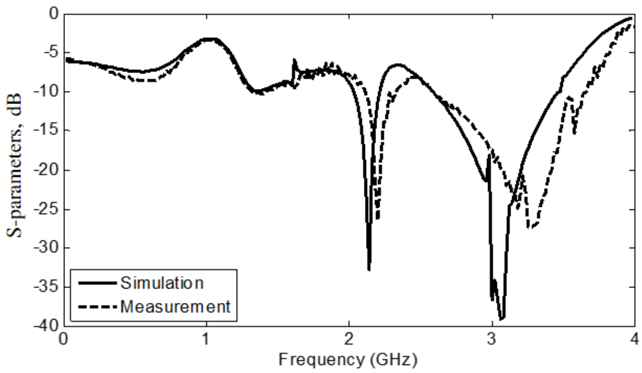

Fig. 6. Performance of 2.69 GHz branch-line coupler $|S_{21}|$.

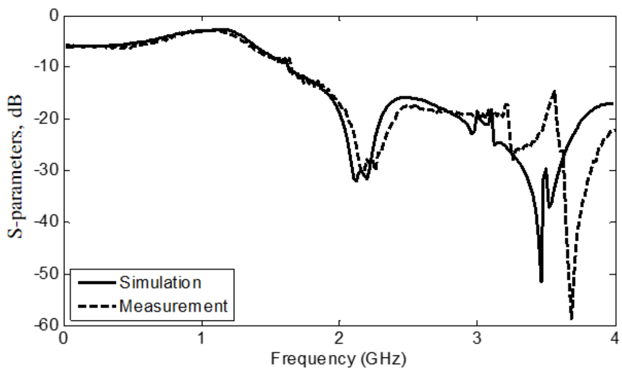

Fig. 7. Performance of 2.69 GHz branch-line coupler $|S_{31}|$.

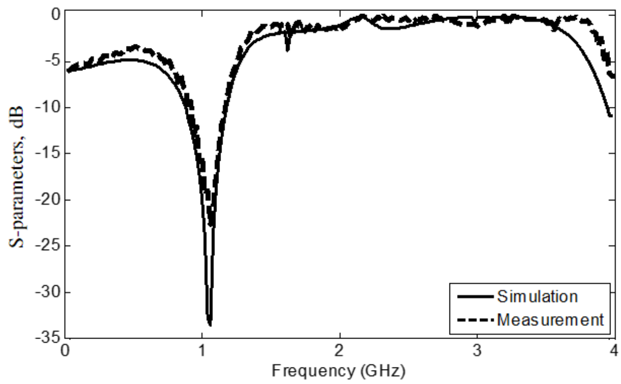

Fig. 8. Performance of 2.69 GHz branch-line coupler $|S_{11}|$.

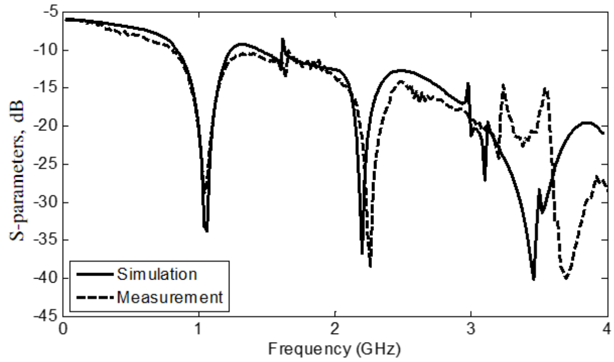

Fig. 9. Performance of 2.69 GHz branch-line coupler $|S_{41}|$.

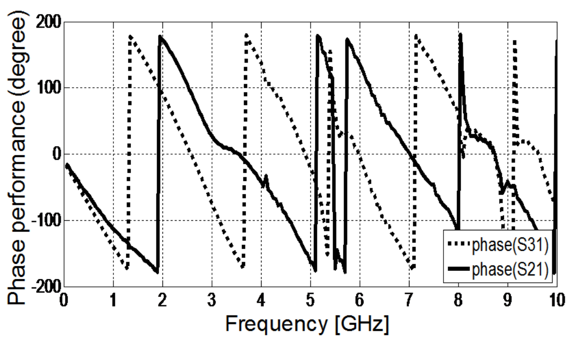

Fig. 10. The phase performance of the proposed structure.

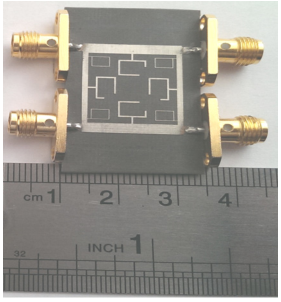

Fig. 11. The photograph of the proposed branch-line coupler.

circuit size has been made by employing the two resonators, i.e. resonator 1 with its open-loop patch and the second resonator with closed-loop patch, which increase the total inductance and capacitance loaded on each traditional quarter-wave length transmission lines. Therefore, the circuit size of the proposed coupler could reduce because the propagation constant, i.e. β enhances ($\beta_{\text{proposed}} / \beta_{\text{conventional}}$ is about 1.50065). The relationship for β is given by:

$$\beta = \omega\sqrt{LC}, \tag{3}$$

$$\beta = \frac{2\pi}{\lambda} \tag{4}$$

where in (3) L refers to the total inductance in per unit length caused by the main transmission line and high impedance lines. C depicts the total capacitance in per unit length of the main transmission line of the branch-line coupler, which is resulted from the employed resonators. In (4) λ determines guided wavelength normalized. The abilities of the proposed circuit and the previous works have been compared, as shown in Tab. 4. The fractal bandwidth of the designed coupler in this work when the S_{11} is less than –15 dB is about 500 MHz, from 2.42 to 2.92 GHz. The photograph of the proposed coupler is illustrated in Fig. 11.

Ref.	Harmonic Suppression	Size reduction
[1]	No	0%
[2]	2nd	72%
[3]	No	55%
[4]	No	63.9%
[5]	No	60%
[6]	2nd	73.2%
[8]	3rd	65%
[9]	No	69%
[10]	No	62%
[11]	No	37%
This work	2nd & 3rd	41%

Tab. 4. The comparison of the abilities of the proposed coupler and previous works.

4. Conclusion

A branch-line coupler using closed-loop and open-loop resonators has been designed and fabricated. Applying these kinds of resonators inside the free area of a branch-line coupler leads to reducing the overall circuit size to about 59% of the conventional case. Furthermore, the proposed structure is able to suppress second and third harmonics based on its frequency response.

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