Novel Compact Branch-Line Coupler Using Non-Uniform Folded Transmission Line and Shunt Step Impedance Stub With Harmonics Suppressions

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Abstract **─** In this paper, a novel compact branch-line coupler (BLC) using non-uniform folded transmission line (NUFTL) and shunt step impedance stubs (SSISs) with harmonics suppressions is presented and its design procedure is discussed. In the proposed structure, in order to reject the unwanted harmonic pass bands, a pair of SSISs is implemented along the ports of the coupler. To minimize the physical size of the coupler, NUFTL are used instead of uniform transmission lines in each arm of the branch-line. With the proposed approach, the size of the quarter-wavelength transmission line in the branch-line can be reduced greatly. The presented BLC has a compact size while showing good return loss and insertion loss characteristic in the frequency band of interest. Good agreement exists between the simulated and measured results.

Index Terms **─** Branch-line coupler (BLC), harmonics suppressions, non-uniform folded transmission line (NUFTL), shunt step impedance stub (SSIS).

I. INTRODUCTION

The compact BLC is an important sub-circuit in microwave integrated circuits and can be used as a power divider/combiner or a part of a mixer [1-5]. The conventional BLC was composed of four quarter-wavelength uniform transmission lines [1]. However, adopting the quarter wavelength transmission line to design the coupler takes too much space; therefore, larger circuit area may result in higher cost. The lumped-element approach [2], which uses spiral inductors and lumped capacitors, is one of the solutions to this problem. Nevertheless, using the lumped element in the circuit design requires an empirical model, such as an inductor model, attained via precise measurement. Mainly, two different approaches have been used to reduce the size of the conventional hybrids. One is to use transmission-line meandering to approximate quarter-wave transmission-line behavior over a certain bandwidth. The other is to use a distributed element approach for the same purpose [3-13]. Multiple shunted open stubs [5] or S-shaped structure loading [8] are well-known methods of miniaturization. The level of miniaturization is determined by the number of meander sections (shunt stubs) and the tightness of the meandering. However, each meander section adds some discontinuities. Moreover, tight meandering results in increased parasitic coupling between transmission-line sections [9-10].

In order to satisfy the compact requirement of the modern wireless systems, several miniaturized techniques [4-14] were proposed to miniaturize the circuit size of the BLC, such as using quasi-lumped elements approach with symmetrical or nonsymmetrical T-shaped structures [4], multiple shunted open stubs [5], compact ring BLC using nonuniform transmission line [6], and step impedance transmission lines (SITLs) [7-8]. A compact slow-wave microstrip BLC with four microstrip high-low impedance resonant cells which were periodically placed inside the BLC was introduced in [9-10]. Furthermore, the conventional coupler has spurious harmonics responses at the harmonics of the

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fundamental frequency, which affects the circuit performance when used in microwave applications. Recently, several design techniques have been reported for size reduction and harmonics suppression [11-13]. In [11], transmission phase characteristic of the BLC is used to increase the bandwidth of inter-band attenuation between the two operating frequencies as well as to reduce the size. Planar artificial transmission line concept is another option to reduce the physical length of a transmission line. In this method, a transmission line incorporated with microstrip quasi-lumped elements is capable of synthesizing microstrip lines with reduced physical length, which can be used to reduce the size of BLC [12]. In [13], to realize multiband operations, a Pi-type-based multiband transmission line network with open- and short-ended stubs was employed. In [14], L-shaped conductor backed asymmetric coplanar stripline and U-shaped conductor backed coplanar waveguide BLC fed by microstrip transmission line have been used. In [15], wideband BLC with symmetrical four-strip is introduced.

This paper presents a novel compact BLC using NUFTL and SSISs with harmonics suppressions. In the proposed structure, in order to reject the unwanted harmonic pass bands, a pair of SSISs is implemented along the ports of the coupler. To minimize the physical size of the coupler, NUFTL are utilized instead of uniform transmission lines in each arm of branch-line. The occupied size of the proposed broadband BLC is merely 45.77% of the size of a conventional design. Simulated and measured results are presented to validate the usefulness of the proposed coupler structure for microwave integrated circuits applications. The proposed BLC structure and its design approach is discussed and illustrated in the following sections.

II. BLC DESIGN AND CONFIGURATION

The novel compact BLC with harmonics suppressions fed by a 50-Ω microstrip line is shown in Fig. 1, which is printed on a RO4003 substrate with permittivity of 3.55, thickness of 0.508 mm, and loss tangent of 0.0027. The basic BLC structure consists of NUFTL and SSISs. In this paper, miniaturization of the BLC is achieved by means of NUFTL located on the branch and through lines of the conventional coupler, and also four SSISs that placed inside the free area of a conventional BLC which are parallel with the conventional coupler's main transmission lines. The proposed BLC is connected to a 50 Ω SMA connector for signal transmission. The presented BLC operates over 2.06–2.81 GHz with $S_{11} < -10$ dB. The planar BLC with various design parameters was constructed, and the numerical and experimental results of the S-parameters and phase characteristics are presented and discussed. The parameters of the proposed BLC are studied by changing one parameter at a time while others were kept fixed. The simulated results are obtained using Ansoft simulation software high-frequency structure simulator (HFSS) [17]. In simulation studies the maximum number of passes and the maximum delta S were chosen 20 and 0.02 respectively. Increasing the mesh density will increase the accuracy at the cost of increased simulation time, but from certain limit it will not have a considerable effect on the accuracy. The final design parameters of the presented BLC are specified in Table 1.

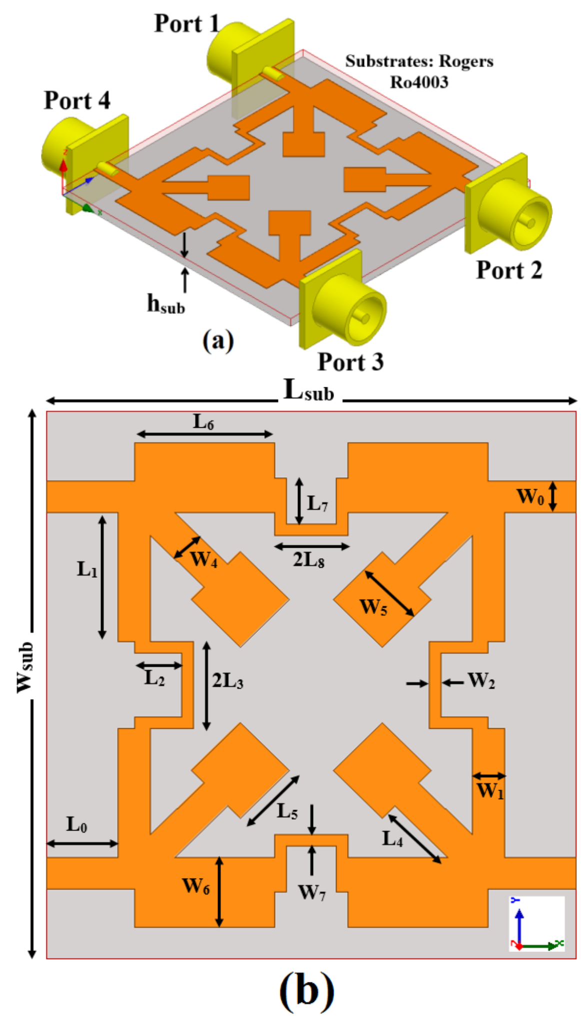
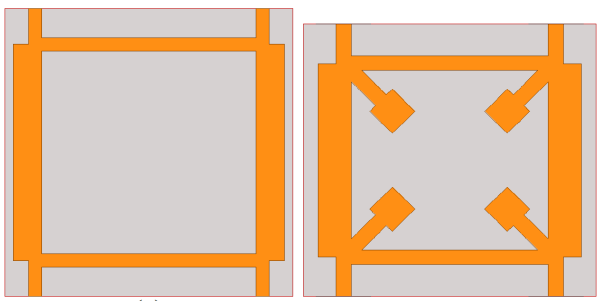


Fig. 1. The geometry of the proposed BLC using NUFTL and SSISs: (a) side view and (b) top view.

Table 1: The final dimensions of the designed BLC

Param.	mm	Param.	mm	Param.	mm
W_{sub}	19	W_6	2.4	L_3	1.5
W_0	1.1	W_7	0.4	L_4	2.5
W_1	1.1	L_{sub}	18	L_5	2.3
W_2	0.4	L_0	2.5	L_6	4.7
W_4	1.1	L_1	4.5	L_7	1.6
W_5	2.3	L_2	1.6	L_8	1.2

Figure 2 shows various BLC structures which were used for simulation studies. $|S_{11}|$ characteristics for conventional BLC (with four quarter-wavelength uniform transmission lines) (Fig. 2 (a)) and the BLC using SSISs (Fig. 2 (b)) are compared in Fig. 3. As shown in Fig. 3, for the proposed BLC configuration, in order to reject the unwanted harmonic pass bands, a pair of SSISs is implemented along the ports of the coupler. Moreover, the four SSISs that are placed inside the free area of conventional BLC play an important role in the miniaturization of the BLC.



(a) **(b)**

Fig. 2. The various BLC structures which were used in simulation studies: (a) the conventional BLC (with four quarter-wavelength uniform transmission lines), and (b) the BLC using SSISs.

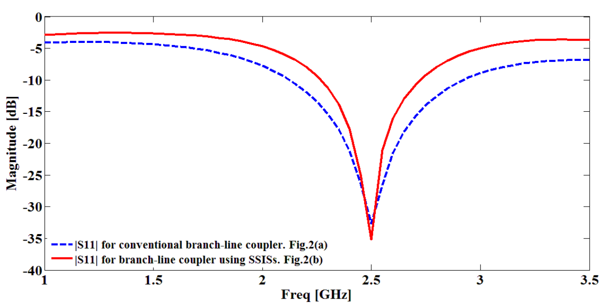


Fig. 3. The $|S_{11}|$ characteristics for BLC structures shown in Figs. 2 (a) and (b).

In general, the conventional BLC is composed of one pair of vertical Z_0 quarter-wavelength microstrip lines and one pair of horizontal 0.707 Z_0 quarter-wavelength microstrip lines, where Z_0 represents the 50 Ω characteristic impedance of the transmission line [1] as shown in Fig. 2 (a). When it is applied for variable attenuators and phase shifters, it would produce higher order harmonics [7-8]. In the design of a conventional BLC, these harmonics are unable to be suppressed. The total size of the conventional BLC is 23.8×20.2 mm^2, as shown in Fig. 2 (a). The conventional BLC, therefore, can hardly be realized due to its large size and because it is not easily implemented in system integration. Thus, the size of the conventional BLC must be reduced. This type of SSISs will introduce four step impedance stubs which are parallel with the conventional coupler's main transmission lines. As the inductances caused by the high-impedance lines of SSISs are only loaded at the sites connected to the ports and in a lumped form, we ignore its influence on the per unit length inductance of the main transmission lines between two adjacent ports. The capacitances caused by the low-impedance lines of SSISs are loaded parallel with the main transmission lines between two adjacent ports and in a distributed form [9-10]. This will increase the per unit length capacitance of the main transmission lines between two adjacent ports. Thus, this type of slow-wave loading here will mainly increase the shunt capacitance of the coupler. An increased propagation constant means that a shorter physical structure can be used to yield a required electrical length compared with a conventional transmission line [9-11]. The SSISs then act similar to a band stop filter at the second and third harmonics frequencies [7-8]. Therefore, the proposed compact BLC shows better microwave performance in case of harmonics rejection in comparison with the conventional BLC. The proposed miniaturization technique achieves 66.1% of size reduction compared to the conventional implementation, (19.6×16.2 mm^2), as shown in Fig. 2 (b).

The even and odd mode decomposition method can be used for a symmetrical four-port network analysis [16], [18-19]. Figure 6 shows the even and odd mode equivalent circuits of the proposed BLC [1]. Voltage (current) vanishes along the symmetrical plane at odd-mode (even-mode) excitation which leads to transmission line equivalent circuits which are depicted in Figs. 6 (a) and (b). In these figures, Y_i are the microstrip line characteristic admittances which are dependent on their corresponding microstrip line width in Fig. 1, and the θ_i are the electrical lengths which are dependent on their corresponding microstrip line length in Fig. 1. For odd-mode excitation the voltage distribution is null along the symmetrical plane and as a result the equivalent circuit in Fig. 6 (b) is applicable [18-19]. As shown in Fig. 6, these cascaded lines and stubs can be analyzed by the ABCD matrix method. In the four-port coupler, the following amplitude and phase conditions should be satisfied [16]:

$$|S_{21}| = |S_{31}|, \tag{1a}$$

$$S_{41} = 0, \tag{1b}$$

$$\angle S_{21} - \angle S_{31} = \pm 90^\circ. \tag{1c}$$

In the even and odd mode circuits, the ABCD matrix can be presented as follows [16]:

$$[ABCD]_o = T_{SC} T_S T_L T_S T_{SC}, \tag{2a}$$

$$[ABCD]_e = T_{OC} T_S T_L T_S T_{SC}, \tag{2b}$$

$$T_S=\begin{bmatrix}\cos\theta_4 & jY_4^{-1}\sin\theta_4\\ jY_4\sin\theta_4 & \cos\theta_4\end{bmatrix}\begin{bmatrix}1 & 0\\ jY_5\tan\theta_5 & 1\end{bmatrix}, \quad (3a)$$

$$T_L=T_{L1}T_{L2}T_{L1}, \quad (3b)$$

$$T_{L1}=\begin{bmatrix}\cos\theta_6 & jY_6^{-1}\sin\theta_6\\ jY_6\sin\theta_6 & \cos\theta_6\end{bmatrix}, \quad (3c)$$

$$T_{L2}=\begin{bmatrix}\cos(2\theta_7+2\theta_8) & jY_7^{-1}\sin(2\theta_7+2\theta_8)\\ jY_7\sin(2\theta_7+2\theta_8) & \cos(2\theta_7+2\theta_8)\end{bmatrix}, \quad (3d)$$

$$T_{SC}=\begin{bmatrix}\cos\theta_1 & jY_1^{-1}\sin\theta_1\\ jY_1\sin\theta_1 & \cos\theta_1\end{bmatrix}\begin{bmatrix}1 & 0\\ -jY_2\cot(\theta_2+\theta_3) & 1\end{bmatrix}, \quad (3e)$$

$$T_{OC}=\begin{bmatrix}\cos\theta_1 & jY_1^{-1}\sin\theta_1\\ jY_1\sin\theta_1 & \cos\theta_1\end{bmatrix}\begin{bmatrix}1 & 0\\ jY_2\tan(\theta_2+\theta_3) & 1\end{bmatrix}. \quad (3f)$$

The subscripts e and o represent the even and odd mode, and also T_S, T_L, T_{SC}, T_{OC} represent the SSIS, NUFTL, short step impedance stub in odd mode and open step impedance stub in odd mode, respectively. From (2) and (3), we can obtain the reflection (Γ) and transmission coefficients (T) [1]:

$$\Gamma_{e,o}=\frac{A_{e,o}+B_{e,o}-C_{e,o}-D_{e,o}}{A_{e,o}+B_{e,o}+C_{e,o}+D_{e,o}}, \quad (4a)$$

$$\mathrm{T}_{e,o}=\frac{2}{A_{e,o}+B_{e,o}+C_{e,o}+D_{e,o}}. \quad (4b)$$

The magnitudes of S-parameter of the BLC at each port can be expressed as [1]:

$$S_{11}=\frac{1}{2}\left(\Gamma_e+\Gamma_o\right), \quad (5a)$$

$$S_{12}=\frac{1}{2}\left(\mathrm{T}_e+\mathrm{T}_o\right), \quad (5b)$$

$$S_{13}=\frac{1}{2}\left(\mathrm{T}_e-\mathrm{T}_o\right), \quad (5c)$$

$$S_{14}=\frac{1}{2}\left(\Gamma_e-\Gamma_o\right). \quad (5d)$$

Since the proposed BLC is symmetrical, the even-odd method is utilized. The voltage (current) is null along the symmetry plane which leads to the transmission line models depicted in Figs. 4 (a), (b) [3]. The presented coupler is analyzed theoretically based on Equations (2-5) and by means of MATLAB software. Because of the discontinuities in the microstrip lines (step discontinuities), associated fringe capacitance, and the changes in the frequency, the simulation and theoretical results differ from each other. The characteristic impedance (Z_i), and the effective permittivity of the transmission lines (ε_{eff}) must be determined in order to be used in theoretical calculations. The Equation (6) from [20] is used in order to determine these two parameters and the calculated (ε_{eff}, Z_i) for the Y_1, Y_2, Y_3, Y_4, Y_5, Y_6, Y_7 lines are (2.76, 50.56 Ω), (2.56, 82.25 Ω), (2.76, 50.56 Ω), (2.95, 30.69 Ω), (2.96, 29.74 Ω), (2.56, 85.25 Ω), respectively.

$$\varepsilon_e=\frac{\varepsilon_r+1}{2}+\frac{\varepsilon_r-1}{2}\left[\left(1+12\left(\frac{H}{W}\right)\right)^{-1/2}+0.04\left(1-\left(\frac{W}{H}\right)\right)^2\right]\ when\left(\frac{W}{H}\right)<1, \quad (6a)$$

$$\varepsilon_e=\frac{\varepsilon_r+1}{2}+\frac{\varepsilon_r-1}{2}\left(1+12\left(\frac{H}{W}\right)\right)^{-1/2}\quad when\left(\frac{W}{H}\right)\geq 1, \quad (6b)$$

$$Z_0=\frac{60}{\sqrt{\varepsilon_{eff}}}\ln\left(8\frac{H}{W}+0.25\frac{W}{H}\right)(ohms)\quad when\left(\frac{W}{H}\right)<1, \quad (6c)$$

$$Z_0=\frac{120\pi}{\sqrt{\varepsilon_{eff}}\left[\frac{W}{H}+1.393+\frac{2}{3}\ln(\frac{W}{H}+1.44)\right]}(ohms)\ when\left(\frac{W}{H}\right)\geq 1. \quad (6d)$$

The frequency response of the equivalent BLC structures in Fig. 4 for the even and odd modes with the parameters values in the Table 1 is depicted in Fig. 5 (a). In these calculations the transmission matrix of the feed lines (W_0 and L_0) are applied to the Equation (2). As can be observed, the even and odd mode structures have different operating frequency bands. Figure 5 (a) shows the calculated frequency response for the BLC in Fig. 1 and based on Equation (5). The obtained results for the equivalent circuit can be used for determination of the frequency response of the structure and bandwidth effects. In other words, they are useful in order to calculate the effect of the parameters on the resonance frequency and the bandwidth. Also, a parametric study is done on the design parameters and the achieved results show that the W_1 and W_6 have the main effect on the operating frequency band while L_7 and L_8 have the least effect.

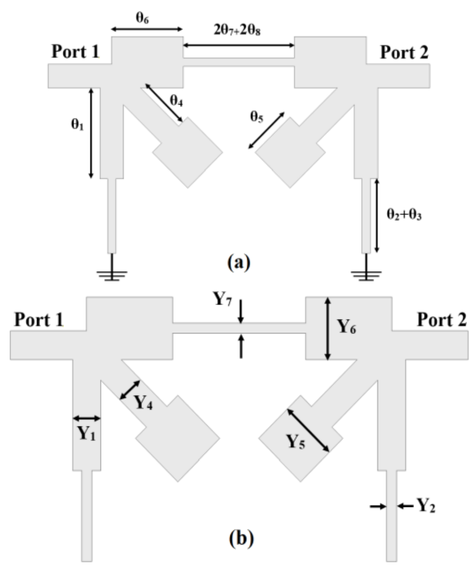
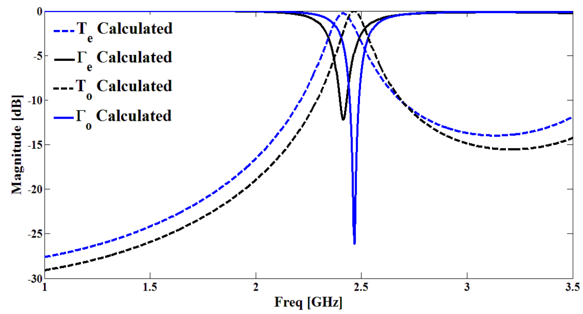
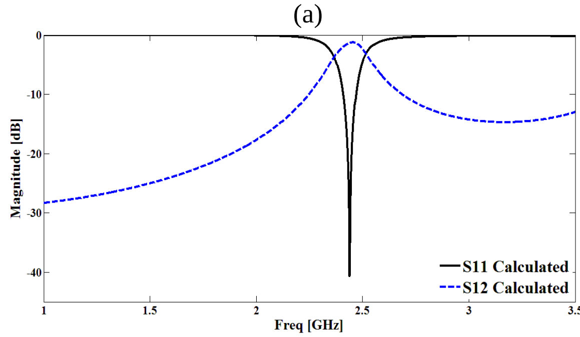


Fig. 4. Proposed BLC using NUFTL and SSISs: (a) odd-mode equivalent circuit, and (b) even-mode equivalent circuit.



(a)



(b)

Fig. 5. Calculated frequency responses for BLC structures with MATLAB software: (a) odd mode and even mode responses for equivalent circuits in Fig. 4 with Equation (4), and (b) proposed BLC with Equation (5).

The transmission line (TL) equivalents for the odd and even modes are shown in Fig. 6 (a) and Fig. 6 (b), respectively. The voltage (current) is null along the symmetry plane in the odd mode (even mode) and as the result the TL equivalent in Fig. 6 (a) (Fig. 6 (b)) is obtained. The step discontinuities in the microstrip lines, the associated fringing capacitance, and also the frequency alteration are considered in simulation studies. The simulated results with HFSS software are depicted in Fig. 7 (a). The simulated results show that the proposed structure has high-pass characteristic at the odd mode and low-pass characteristic at the even mode. These effects lead to a proper out of band rejection which is desirable. The simulated results are similar with the results which were calculated based on the equations (1-5). In Fig. 7 (b), the simulated results for the proposed BLC are presented.

In order to modify the design parameters of the proposed BLC, a parametric study was performed. As examples of the aforementioned parametric study, the effect of two design parameters (W_5 and W_2) are presented and discussed here in Fig. 8 and Fig. 9.

Figure 8 shows the effect of variation in width of the low-impedance line of SSIS (W_5 in Fig. 1 (b)) on the frequency responses of the proposed BLC. It is found that by changing the width of the low-impedance line of SSIS, the position of the frequency band of interest can be adjusted properly. Figure 9 shows the effect of variation in finger width of the vertical arm of the NUFTL (W_2 in Fig. 1 (b)) on return loss characteristic of the proposed BLC for different cases. As it can be observed from this figure, the impedance bandwidth can be fine-tuned effectively by modifying this parameter. Another effective way to reduce the size of a BLC is the replacement of straight transmission lines segments by space-filling curve segments with the same electrical characteristics [5-6]. Moreover, nonuniform transmission line can be used instead of the quarter wavelength uniform transmission lines to reduce the size of BLC. In this method, the normalized width function of the nonuniform transmission lines is expanded in a truncated Fourier series and an optimization method applied to obtain the optimum values of the series coefficients. Generally, step impedance transmission line is a non-uniform transmission line, which can be used in microstrip circuits for size reduction, shift the spurious pass band to the higher frequency and even to suppress the multiple spurious pass bands [6-7].

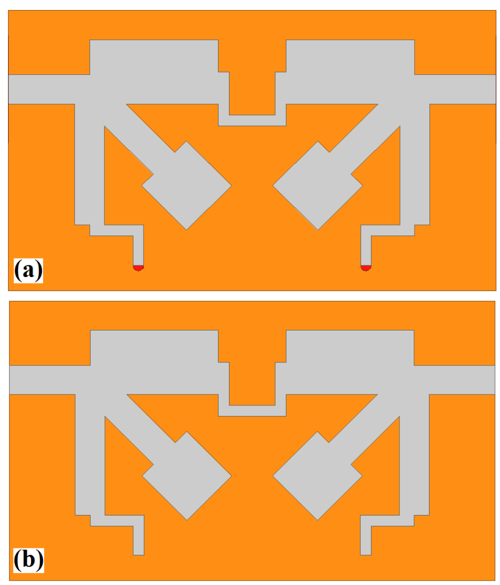
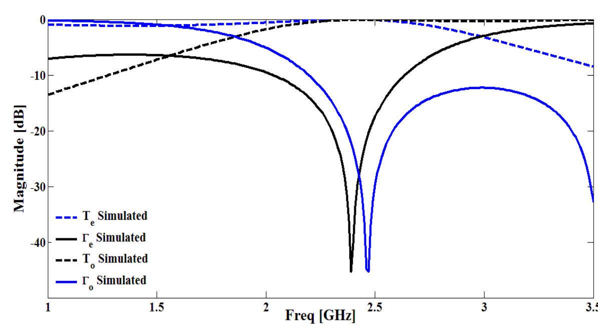
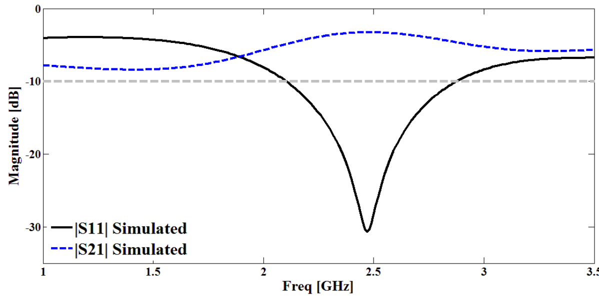


Fig. 6. Proposed BLC using NUFTL and SSISs: (a) odd-mode equivalent-TL, and (b) even-mode equivalent-TL.



(a)



(b)

Fig. 7. Simulated frequency responses for BLC structures with HFSS software: (a) odd mode and even mode responses for equivalent-TL circuits in Fig. 6, and (b) proposed BLC in Fig. 1.

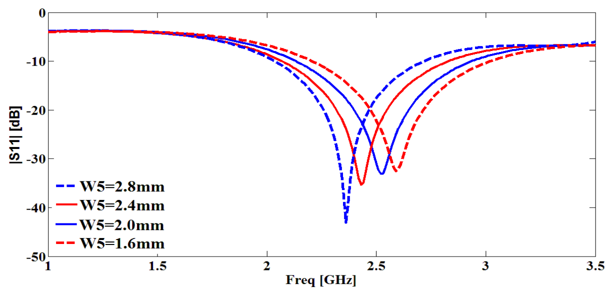


Fig. 8. The effect of variation in width of the low-impedance line of SSIS (W_5 in Fig. 1 (b)) on $|S_{11}|$.

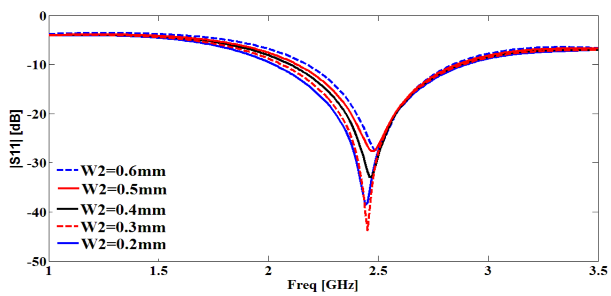


Fig. 9. The effect of variation in finger width of the vertical arm of the NUFTL (W_2 in Fig. 1 (b)) on $|S_{11}|$.

III. RESULTS AND DISCUSSIONS

The proposed BLC with final design parameters, as shown in Fig. 10, was fabricated and tested. All measured and simulated results of the fabricated BLC are shown in Fig. 11 and Fig. 12. From Fig. 11 (a), it can be confirmed that the proposed BLC has a wide bandwidth of 32% (2.06–2.81 GHz, centre frequency = 2.40 GHz) at the reference -10 dB reflection coefficient for all ports. In the operating bandwidth the isolation between port 1 and port 4 is more than 25 dB. The measured $|S_{21}|$ and $|S_{31}|$ at the center frequency are -3.3 dB and -3.4 dB, respectively. There exists good agreement between simulation and measurement results.

Figure 12 shows the measured phase responses. There exists a discrepancy between the measured data and the simulated results. Simulated phase difference between port 2 and port 3 is 90° ± 2° at the operating bandwidth.

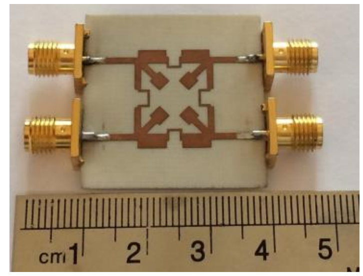


Fig. 10. Photograph of the fabricated BLC prototype with NUFTL and SSISs.

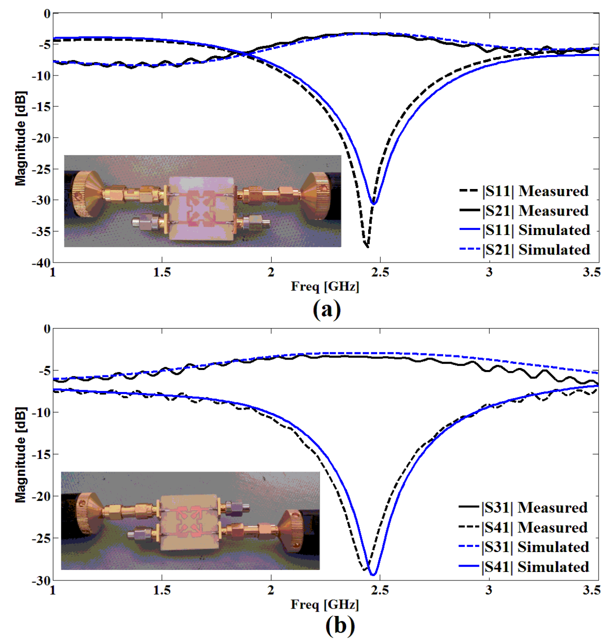


Fig. 11. Measured and simulated frequency responses of the fabricated BLC using NUFTL and SSISs shown in Fig. 1.

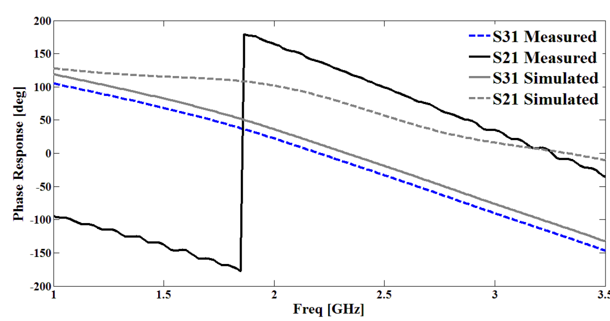


Fig. 12. Measured and simulated phase responses of the fabricated BLC using NUFTL and SSISs shown in Fig. 1.

As shown in measured results, there exists a discrepancy between the measured data and the simulated results. The discrepancy is mostly due to a number of parameters such as the fabricated BLC dimensions as well as the thickness and dielectric constant of the substrate, on which the BLC is fabricated. In order to confirm the accurate return loss characteristics for the designed BLC, it is recommended that the manufacturing and measurement processes need to be performed carefully; besides, SMA soldering accuracy and substrate quality need to be taken into consideration [21-22]. In summary, it can be said that a fine agreement between the measured and the simulated results is obtained in the frequency band of operation.

Finally, a comparison between the proposed BLC and other coupler structures with same characteristics which have been published in literature and used here as references is presented in Table 2. From this table, it can be concluded that the proposed BLC has improved in-band and out-of-band performances as well as size miniaturization. In comparison with [6] and [12], the proposed BLC has a smaller size, with respect to the operating frequency band. The presented BLC has a wider bandwidth in comparison with the BLCs in [4-7] and [9-10]. The out-of-band performance of the presented BLC is better than the ones in [4, 7, 10]. Moreover, the realization of the proposed BLC is simpler than the ones in [6, 7, 12, 14].

Table 2: A comparison among the proposed BLC using NUFTL and SSISs and the previous work

Ref.	f_0 (GHz)	FBW 10 dB(%)	ε_r/h (mm)	Size ($\lambda_0 \times \lambda_0$)
[3]	1	30	2.2/1.58	0.112×0.098
[4]	2.4	25	4.7 /0.80	0.074×0.095
[5]	2.4	22	4.3/0.80	0.117×0.087
[6]	2	25	2.2/0.508	0.272×0.128
[7]	1	28	3.55/0.76	0.233×0.257
[8]	5	40	4.4/0.80	0.087×0.091
[9]	2	10	2.1/0.508	0.130×0.130
[10]	0.836	12	4.2/1.02	0.221×0.207
[12]	2.4	33	3.38/0.813	0.159×0.192
[14]	2	26	10.2/1.27	0.092×0.090
This work	2.4	32	3.55/0.508	0.096×0.115

f_0: Centre frequency of operation band; ε_r: Substrate relative dielectric constant; h: Substrate thickness; λ_0: the free space wavelength of the operating frequency at the center of the pass-band (2.40 GHz).

IV. CONCLUSION

A novel compact BLC was presented and discussed. The presented BLC consists of a NUFTL and SSISs in order to obtain wideband characteristic, which is able to suppressing higher order harmonics of the BLC over a wideband. The BLC exhibits low insertion loss over the desired passband and sufficient isolation level at the frequency band of interest. Good agreement exists between the simulated and measured results.

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