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A Broadband Balun With Complex Impedance Transformation and High Isolation

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ABSTRACT The design of baluns with wide bandwidth, transformation between complex source and load impedances, and high isolation is presented in this paper. These features can be accomplished simultaneously by employing double-stub couple lines (DSCL). The differential characteristics are established by only exciting the odd-mode operation of the balun, and suppressing its even-mode operation. For the odd-mode operation, the structure of the DSCL acts as a multi-stub structure and contributes to bandwidth enhancement. An additional resistor added to the DSCL between the output ports improves their isolation and contributes to the impedance transformation. An experiment was prepared for the operations of the proposed design at 2.8 GHz with $Z_S = 35 - j10\ \Omega$ and $Z_L = 60 + j10\ \Omega$. A measured wide bandwidth of 35% was obtained under the criterions of $|S_{11}| < -10$ dB, $(\angle S_{31} - \angle S_{21}) < 180° \pm 5°$, and $(|S_{31}| - |S_{21}|) < 1$ dB.

INDEX TERMS Broadband balun, coupled line, high isolation, complex impedance transformation.

I. INTRODUCTION

In recent years, more and more professionals have chosen differential-in designs for wireless circuits because the designs provide the advantages of immunity to noises and interferences. The differential signals can be generated through baluns, which convert a single-ended unbalanced signal into two differential-in balanced signals. Many applications require baluns with advanced functions such as compact size, broadband or multi-band operations, real or complex impedance transformations, high isolation, and filtering characteristics, which has initiated a great deal of research activities on topics related to advanced baluns.

There have been quite a few designs for advanced baluns from recent publications [1]–[16]. In [1], a branch-line coupler with an open isolated port can provide differential signals by connecting an open stub to the middle of each lateral transmission line. The balun can conduct impedance transformation, but lacks isolation. A dual-band balun was constructed by four pairs of parallel coupled lines and six open stubs [2], which can offer the function of impedance transformation. However, the conversion is only applicable to real impedances. In [3], the combination of three pairs of coupled lines, two open stubs, and resistors produces a compact balun capable of transforming complex impedances. A lumped balun with complex impedance transformation was designed based on an asymmetric modification of the out-of-phase-compensated power splitter topology [4]. However, the lumped elements fail to function properly at higher frequencies. In [5], the function of tunable power division ratio was achieved by modifying the conventional Marchand balun with a varactor and a resistor added to the middle of two pairs of coupled lines. A Marchand balun with open-circuited ends and a capacitive feeding can reduce its length to around 1/3 compared with the conventional design [6]. The stacked composite resonators [7] and coupled half-wavelength microstrip resonators [8], were developed for designs of filtering baluns. The designs explored in [9], [10] are based on the Wilkinson power dividers. The property of 180° phase shift between two output signals is achieved by replacing one of the $\lambda/4$ transmission lines with a $3\lambda/4$ line or its substitutes. The designs can achieve high isolation.

As to bandwidth enhancement, multi-section designs would produce more bandwidth, but the prices are large size and the need for high-impedance lines. In [11], a broadband

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balun with vertical transition between conductor-backed coplanar waveguide and parallel-strip transmission line was presented. In [12], a broadband balun constructed from a broadband phase inverter presented in parallel strips and a broadband impedance matching network with short-circuited stubs was demonstrated. A planar balun consisting of a broadband Wilkinson power divider and a noncoupled-line broadband 180° phase shifter was developed in [13]. In [14], a new design methodology was presented to improve the bandwidth of a Marchand balun. In [15], a balun based on an artificial fractal-shaped composite right/left-handed transmission line was developed for bandwidth enhancement and size reduction. In [16], a lumped-element balun developed from an asymmetrical four-port network with a tail inductor was proposed. All those broadband baluns [11]–[16] do not possess function of impedance transformation.

As shown above, the advanced baluns can be improved in three aspects. First, the bandwidth enhancement of baluns is important for broadband communication applications. Second, the balun featuring complex impedance transformation can significantly reduce system size due to the direct connection between the balun and the complex ports of external devices. Third, the balun with high isolation plays an important role in the balance circuits to prevent signal interference.

To achieve these three design goals simultaneously, a balun featuring wide bandwidth, transformation of complex impedances, and high isolation is proposed in this paper. The double-stub couple line (DSCL) is applied to the balun. By suppressing its even-mode operations, the odd-mode operations lead the two outputs out of phase by 180°. For the odd-mode operation, the structure of the DSCL acts as a multi-stub structure and contributes to bandwidth enhancement. An isolation resistor introduced between the output ports further establishes the function of transformation of complex impedances and the property of high isolation. The details of this design are disclosed in the follow-up sections. Section II provides the analysis for the broadband balun featuring transformation of complex impedances and high isolation. The experimental verification and discussion are presented in Section III. The results show superior performance on complex impedance transformation, high isolation, and wide bandwidth. At the end, a conclusion for this study is prepared.

II. BROADBAND BALUN FEATURING TRANSFORMATION BETWEEN A COMPLEX SOURCE AND A COMPLEX LOAD IMPEDANCES

In this section, a balun is developed for broadband applications, which is also capable of conducting transformation between a complex source and a complex load impedances. The broadband property of the proposed design is contributed by the DSCL shown in Fig. 1, which is derived from a λ/4 transmission line, as described in [17]. The DSCL consists of a main transmission line (Z_A, θ_A) and a parallel

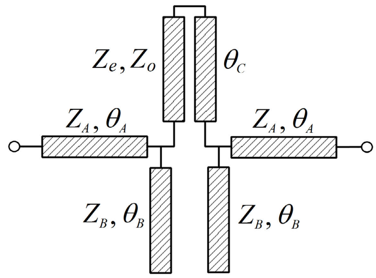

FIGURE 1. The circuit model for the double-stub coupled line (DSCL).

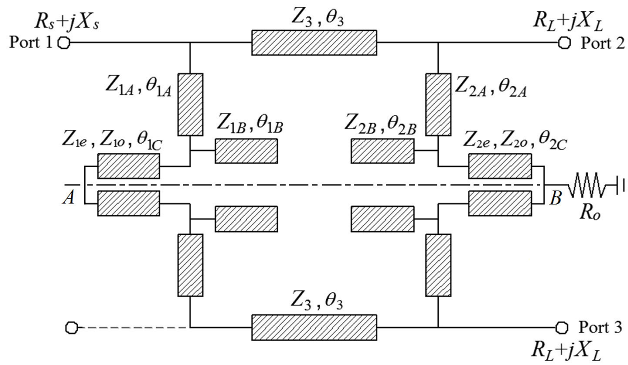

FIGURE 2. The circuit model for the proposed balun using the DSCLs.

coupled line (Z_e, Z_o, θ_C) connected to the middle of the main line. The two lines of the coupled line are short to each other at one end, and are connected to two open stubs (Z_B, θ_B), respectively, and the main line at the other end. Fig. 2 illustrates the circuit model for the proposed balun, in which the DSCLs are used to replace the lateral λ/4 transmission lines of a branch-line coupler to establish a broadband balun. The design parameters of the DSCL can be managed to only allow its odd-mode operation, and to suppress its even-mode operation to obtain differential output signals. For the odd-mode operation, the structure of the DSCL is reduced to a stepped-impedance line short to ground at one end and tapped with an open stub in the middle, which acts as a multi-stub structure and contributes to bandwidth enhancement. Note that the proposed DSCL is introduced for a broadband balun featuring complex impedance transformation and high isolation, which differs from the design in [17].

A. EVEN-ODD MODE ANALYSIS

A three-port balun can be implemented by a four-port branch-line coupler with its isolated port left open, as shown in Fig. 2. The advantage of this coupler is its symmetric structure, which allows the application of even- and odd-mode analysis to meet the requirements of broadband property and phase different of 180° between the output ports. In addition, since a three-port device cannot serve as a lossless and reciprocal network with impedance matched at all ports simultaneously,

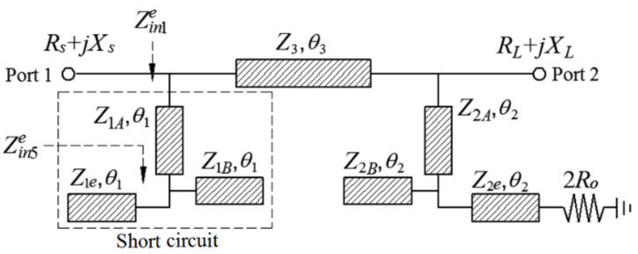

FIGURE 3. The even-mode circuit model for proposed balun.

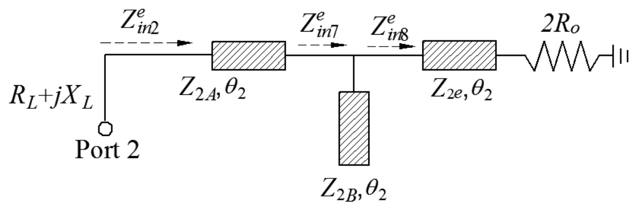

FIGURE 4. The reduced even-mode circuit model with Port 1 short to ground.

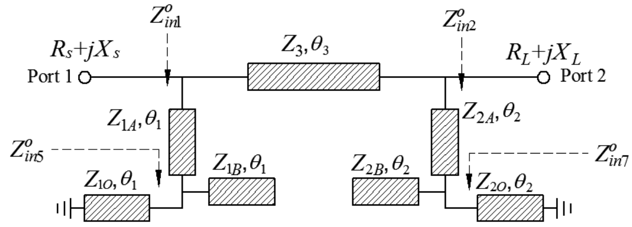

FIGURE 5. The odd-mode circuit model for the proposed balun.

a resistor is introduced between the output ports to achieve the performance of high output isolation, impedance matched at all three ports, and transformation of complex impedances. For a balun featuring above properties, its S parameters must comply with the following conditions:

$$S_{ii} = 0, \quad \text{for } i = 1, 2, \text{and } 3, \tag{1a}$$

$$S_{23} = 0, \tag{1b}$$

$$S_{21} = -S_{31}. \tag{1c}$$

One way to achieve the phase difference of 180° specified in (1c) for a balun design is to disable its even-mode transmission and to preserve its odd-mode operation. The former gives the following:

$$S^e_{21} = 0. \tag{2}$$

Further derivations would lead to the crucial equations below for the even- and odd-mode analysis on the balun[2],

$$S^e_{22} = 0, \tag{3a}$$

$$S^e_{11} + S^o_{11} - 2S^e_{11}S^o_{11} = 0, \tag{3b}$$

where the superscripts e and o represent even- and odd-modes, respectively. The even-mode circuit model of the proposed balun can be obtained from the circuit model given in Fig. 2 with the central dashed line section $A - B$ as a decoupling line, and is shown in Fig. 3. At its even-mode excitation, the left DSCL is required to be a short circuit, and the right DSCL becomes an open-circuited stepped-impedance line (Z_{2A}, Z_{2B}, θ_2) tapped with a series connection of a stub (Z_{2e}, θ_2) and a resistor $2R_o$. The circuit serves as an equivalent complex load to achieve impedance matching and high isolation.

To simplify the circuit design, the electrical lengths, θ_{1A}, θ_{1B}, θ_{1C}, are set to be θ_1; θ_{2A}, θ_{2B}, and θ_{2C} are equal to θ_2; θ_3 is fixed at 90°. The even-mode input impedance in Fig. 3, Z^e_{in1}, can be derived as

$$Z^e_{in1} = Z_{1A}\frac{Z^e_{in5} + jZ_{1A}\tan\theta_1}{Z_{1A} + jZ^e_{in5}\tan\theta_1}, \tag{4a}$$

$$Z^e_{in5} = -j\frac{Z_{1e}Z_{1B}\cot\theta_1}{Z_{1e}+Z_{1B}}. \tag{4b}$$

Z^e_{in1} is set to be zero to satisfy the requirement noted in (2). The even-mode impedance of the coupled line, Z_{1e}, can be obtained from the equations above, and is given by

$$Z_{1e} = \frac{Z_{1A}Z_{1B}\tan\theta_1}{Z_{1B}\cot\theta_1 - Z_{1A}\tan\theta_1}. \tag{5}$$

At the even-mode operation, Port 1 can be considered short to ground since $Z^e_{in1} = 0$. The associated reflection coefficient at Port 1, S^e_{11}, is given below according to [18],

$$S^e_{11} = \frac{-R_S + jX_S}{R_S + jX_S}. \tag{6}$$

The even-mode circuit model in Fig. 3 can be reduced to the one shown in Fig. 4. Based on the condition given in (3a), the even-mode input impedance at port 2, Z^e_{in2}, can be obtained as

$$Z^e_{in2} = R_L - jX_L. \tag{7}$$

The same impedance can be expressed in terms of the circuit elements in Fig. 4, and is given by

$$Z^e_{in2} = Z_{2A}\frac{Z^e_{in7} + jZ_{2A}\tan\theta_2}{Z_{2A} + jZ^e_{in7}\tan\theta_2}, \tag{8a}$$

$$Z^e_{in7} = \frac{Z^e_{in8}Z_{2B}\cot\theta_2}{Z_{2B}\cot\theta_2 + jZ^e_{in8}}, \tag{8b}$$

$$Z^e_{in8} = Z_{2e}\frac{2R_o + jZ_{2e}\tan\theta_2}{Z_{2e} + j2R_o\tan\theta_2}. \tag{8c}$$

The combination of (7) and (8) leads to solutions for Z_{2e} and R_o, from which Z_{2e} and R_o become a function of R_L, X_L, Z_{2A}, Z_{2B}, and θ_2. A root searching program is applied to simplify the process to determine Z_{2e} and R_o.

Solutions for the odd-mode impedances Z_{1o} and Z_{2o} are treated differently. Fig. 5 shows the odd-mode circuit model for the proposed broadband balun. The *ABCD* matrix of the odd-mode circuit model can be derived as

$$\begin{bmatrix} A_o & B_o \\ C_o & D_o \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ \frac{1}{Z^o_{in1}} & 1 \end{bmatrix} \cdot \begin{bmatrix} \cos\theta_3 & jZ_3\sin\theta_3 \\ j\frac{\sin\theta_3}{Z_3} & \cos\theta_3 \end{bmatrix} \cdot \begin{bmatrix} 1 & 0 \\ \frac{1}{Z^o_{in2}} & 1 \end{bmatrix} = \begin{bmatrix} j\frac{Z_3}{Z^o_{in2}} & jZ_3 \\ j(\frac{1}{Z_3} + \frac{Z_3}{Z^o_{in1}Z^o_{in2}}) & j\frac{Z_3}{Z^o_{in1}} \end{bmatrix}_{\theta_3=90^o} \quad (9)$$

where Z^o_{in1} and Z^o_{in2} are the input impedances of the odd-mode circuit models for the DSCLs near Port 1 and Port 2, respectively, and are given by

$$Z^o_{in1} = Z_{1A}\frac{Z^o_{in5} + jZ_{1A}\tan\theta_1}{Z_{1A} + jZ^o_{in5}\tan\theta_1}, \quad (10a)$$

$$Z^o_{in2} = Z_{2A}\frac{Z^o_{in7} + jZ_{2A}\tan\theta_2}{Z_{2A} + jZ^o_{in7}\tan\theta_2}, \quad (10b)$$

$$Z^o_{in5} = \frac{jZ_{1B}Z_{1o}}{Z_{1B}\cot\theta_1 - Z_{1o}\tan\theta_1}, \quad (10c)$$

$$Z^o_{in7} = \frac{jZ_{2B}Z_{2o}}{Z_{2B}\cot\theta_2 - Z_{2o}\tan\theta_2}. \quad (10d)$$

The odd-mode reflection coefficient, S^o_{11}, can be expressed as

$$S^o_{11} = \frac{A_o(R_L+jX_L)+B_o-C_o(R_S-jX_S)(R_L+jX_L)-D_o(R_S-jX_S)}{A_o(R_L+jX_L)+B_o+C_o(R_S+jX_S)(R_L+jX_L)+D_o(R_S+jX_S)} \quad (11)$$

The solutions for the odd-mode impedances, Z_{1o} and Z_{2o}, can be obtained by applying (6) and (9)–(11) into (3b), and their values can be determined through a root searching numerical technique.

B. PARAMETRIC ANALYSIS

Both even- and odd-mode circuit models are π networks with each of their lateral circuits characterized by a stepped-impedance stub tapped with an open-circuited stub in the middle, which would enhance the bandwidth of the balun. The line width and spacing of coupled lines are determined by the values of even- and odd-mode impedances. From the derivation above, the number of design equations is far less than the number of the circuit parameters of the balun. Thus, more choices are offered for the circuit dimensions. This under-determined feature is beneficial to circuit implementation since both line width and spacing of coupled lines are subject to the fabrication limits of PCBs.

The values of the even- and odd-mode impedances of the DSCLs can be determined by conducting a parametric study to observe the variations of Z_{1e}, Z_{1o}, Z_{2e}, and Z_{2o} subject to the changes in θ_1 and θ_2, with other parameters fixed at some values. It can be seen from (5), (7), and (8), that Z_{1e} is mainly influenced by the design parameters of the left DSCL; while Z_{2e} is primarily affected by those of the right DSCL. The impedances Z_{1o} and Z_{2o} exhibit similar dependence as their individual paired impedances Z_{1e} and Z_{2e} do because even- and odd-mode impedances are together to determine the properties of a coupled line. The analysis would be easier if the design parameters of the two DSCLs are treated separately.

TABLE 1. The sixteen impedance sets for the parametric analysis on the proposed balun.

Case I: Z_S = 35–j10 Ω and Z_L = 60+j10 Ω									
Set	A	B	C	D	Set	E	F	G	H
Z_{1A} (Ω)	50	120	55	70	Z_{2A} (Ω)	50	80	70	40
Z_{1B} (Ω)	50	80	80	60	Z_{2B} (Ω)	50	100	90	55
Z_3 (Ω)	60	65	68	62	Z_3 (Ω)	60	65	62	66
Case II: Z_S = 40–j90 Ω and Z_L = 70+j100 Ω									
Set	I	J	K	L	Set	M	N	O	P
Z_{1A} (Ω)	50	120	55	70	Z_{2A} (Ω)	50	80	75	60
Z_{1B} (Ω)	50	80	80	60	Z_{2B} (Ω)	50	100	60	65
Z_3 (Ω)	60	120	110	110	Z_3 (Ω)	60	120	110	80

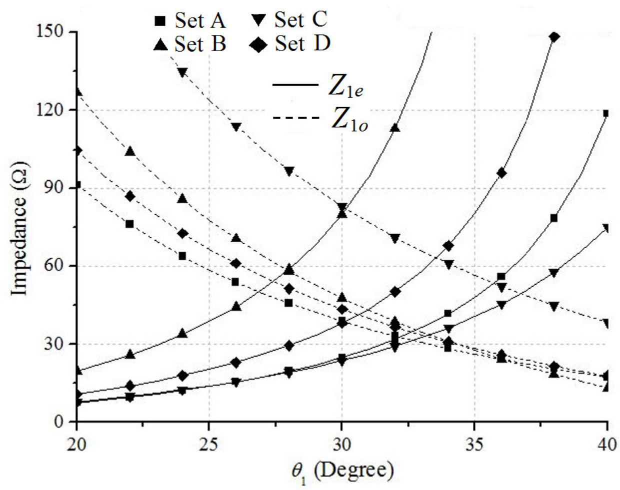

FIGURE 6. The variations of Z_{1e} and Z_{1o} of the left DSCL subject to the changes in θ_1 for Case I ($Z_S = 35 - j10$ Ω and $Z_L = 60 + j10$ Ω).

To simplify the parametric analysis of the even- and odd-mode impedances, the initial values of Z_{1A}, Z_{1B}, Z_{2A}, Z_{2B}, and Z_3 are confined to the numbers specified by sixteen impedance sets (Sets A–P) listed in Table 1. The electrical lengths θ_1 and θ_2 are chosen to be the variables for the analysis. Two combinations of source and load impedances are considered in this work. The pair of $Z_S = 35 - j10$ Ω and $Z_L = 60 + j10$ Ω is denoted by Case I, and the other pair of $Z_S = 40 - j90$ Ω and $Z_L = 70 + j100$ Ω is Case II.

Following the impedance values from Sets A–D, Fig. 6 shows the variations of Z_{1e} and Z_{1o} of the left DSCL subject to the changes in θ_1 for Case I. As indicated in the figure, Z_{1e} increases as θ_1 increases in contrast to Z_{1o},

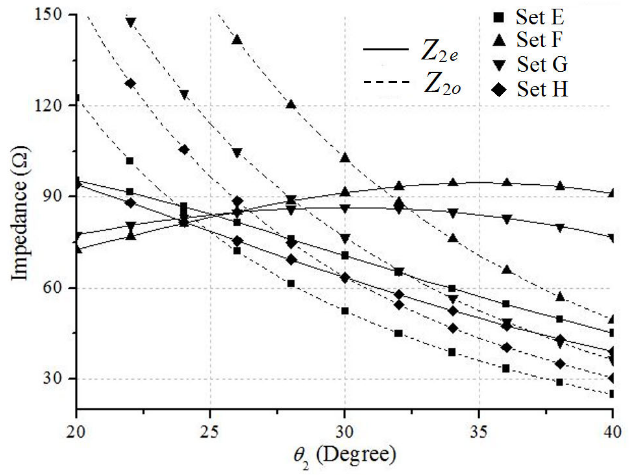

FIGURE 7. The variations of Z_{2e} and Z_{2o} of the right DSCL subject to the changes in θ_2 for Case I ($Z_S = 35 - j10\ \Omega$ and $Z_L = 60 + j10\ \Omega$).

which varies inversely. A larger θ_1 would result in a higher impedance ratio of Z_{1e}/Z_{1o}, which would make the fabrication of coupled lines difficult. A criterion to follow is the value of Z_{1e}/Z_{1o} less than 3. However, when θ_1 is less than 27°, the coupled lines become impractical since the value of the corresponding Z_{1e} is less than that of the paired Z_{1o}. Based on the comparisons made among Sets A–D, a larger Z_{1A} would lead to a larger Z_{1e}; while a larger Z_{1B} could result in a larger Z_{1o}. In summary, the impedance values specified in Set A and a value of 34° for θ_1 are chosen to seek for the appropriate values for Z_{1e} and Z_{1o}. The final selected values for Z_{1e} and Z_{1o} are 41.73 Ω and 31.34 Ω, respectively.

Fig 7 shows the variations of Z_{2e} and Z_{2o} of the right DSCL subject to the changes in θ_2 for Case I. The impedance Z_{2o} varies similarly as Z_{1o} does in Fig. 6; however, Z_{2e} changes differently from Z_{1e} because of the existence of R_o, resulting in irregular curves. The rules to choose the appropriate values for Z_{1e} and Z_{1o} can also apply to the search for the suitable values for Z_{2e} and Z_{2o} by referring to Fig. 7, which suggests the impedance values described by Set F and a value of 36° for θ_2. The appropriate values for Z_{2e} and Z_{2o} are 94.5 Ω and 54.69 Ω, respectively.

Fig. 8 shows the variations of Z_{1e} and Z_{1o} of the left DSCL subject to the changes in θ_1 for Case II. The curves representing Z_{1e} and Z_{1o} for Case II are similar to their counterparts in Fig. 6 for Case I, but with lower impedance values compared to the values in Fig. 6. Therefore, the rules used for Case I can apply to Case II as well to choose the appropriate values for Z_{1e} and Z_{1o} by referring to the design curves in Fig. 8. Fig. 9 shows the variations of Z_{2e} and Z_{2o} versus the changes in θ_2, in which both Z_{2e} and Z_{2o} increase tremendously as θ_2 decreases, much faster than their counterparts do in Fig. 7. Since Z_{2e} and Z_{2o} of higher values may cause the same fabrication problem, a longer θ_2 leading to lower even- and odd-mode impedances is preferred for this case. To transform complex impedances with a large reactance, an increase in Z_3 and a longer θ_2 can help to bring Z_{2e} and Z_{2o} into the feasible range of the coupled line.

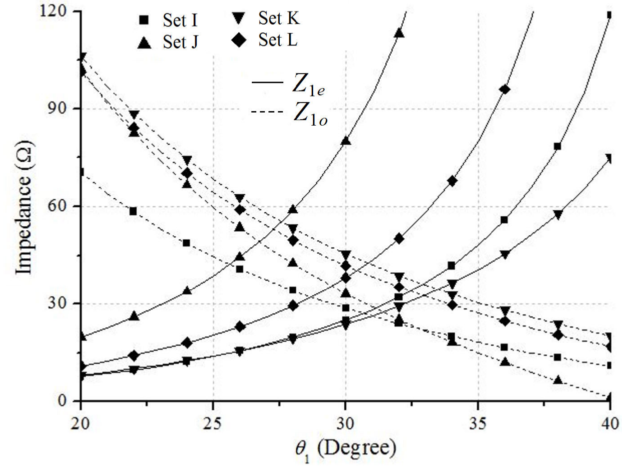

FIGURE 8. The variations of Z_{1e} and Z_{1o} subject to the changes in θ_1 for Case II ($Z_S = 40 - j90\ \Omega$ and $Z_L = 70 + j100\ \Omega$).

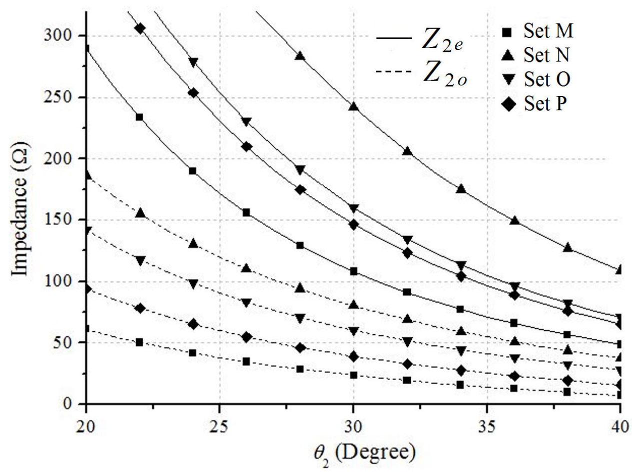

FIGURE 9. The variations of Z_{2e} and Z_{2o} subject to the changes in θ_2 for Case II ($Z_S = 40 - j90\ \Omega$ and $Z_L = 70 + j100\ \Omega$).

To achieve the goals of transformation of complex impedances and high isolation, the right DSCL is loaded with an isolation resistor R_o. Fig. 10 shows the variations of R_o subject to the changes in θ_2 for both Cases I and II. The value of R_o decreases as θ_2 increases. The curves representing Case I vary more slowly than the ones representing Case II do. The values of R_o for all the impedance sets are within the feasible range of 2–60 Ω for implementation. The utmost concern for the proposed design is the values of the even- and odd-mode impedances. As shown in Figs 6–10, there are multiple choices presented for their values, which is one of the advantages offered by this design.

III. EXPERIMENTAL VERIFICATION AND DISCUSSION

The design procedure for the proposed design is summarized as follows.

1) Choose the impedance values from Sets A–P in Table 1 as the initial values for the design parameters of

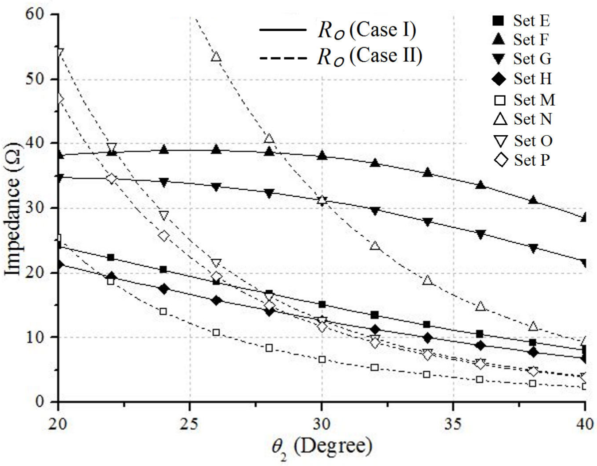

FIGURE 10. The variations of R_o subject to the changes in θ_2 for both Cases I and II.

TABLE 2. The design parameters of the proposed balun.

Z_{1A}	Z_{1B}	Z_{1e}	Z_{1o}	θ_1	Z_{2A}	Z_{2B}
50 Ω	50 Ω	41.73 Ω	31.34 Ω	34°	80 Ω	100 Ω
Z_{2e}	Z_{2o}	θ_2	Z_3	θ_3	R_o	
94.5 Ω	54.69 Ω	36°	62.7 Ω	90°	33.48 Ω	

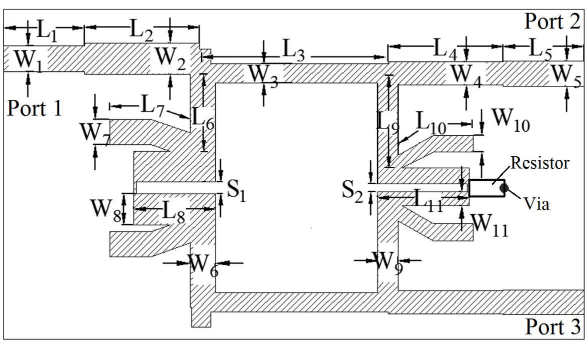

FIGURE 11. The circuit layout for the proposed balun.

the DSCLs with the given values for Z_S and Z_L and a fixed value of 90° for θ_3.

2) The criterion for selecting appropriate even- and odd-mode impedances is the values of Z_{1e}/Z_{1o} and Z_{2e}/Z_{2o} less than 3.

3) Apply (5) and refer to Fig. 6 and Fig. 8 to determine the appropriate values for Z_{1e}, Z_{1A}, Z_{1B}, and θ_1 of the left DSCL and Z_3.

4) Obtain the values of Z_{2e},R_o, Z_{2A}, Z_{2B}, and $\theta_2$from (7), (8), Fig. 7, Fig. 9, and Fig. 10 for the right DSCL.

5) Apply (3b), (6), (9)–(11) and refer to Figs. 6–9 to determine the appropriate values for Z_{1o} and Z_{2o} of the DSCLs.

To validate the proposed design, a design example operating at 2.8 GHz and conducting impedance transformation defined by Case I is presented. The design parameters of the proposed design went through the optimization process

TABLE 3. The dimensions of the circuit from Fig. 11 (all in mm).

L_1	L_2	L_3	L_4	L_5	L_6	L_7	L_8	L_9	L_{10}	L_{11}	S_1
7	10	17	10	7	7.2	7.2	7.2	7.9	7.9	7.9	0.6
W_1	W_2	W_3	W_4	W_5	W_6	W_7	W_8	W_9	W_{10}	W_{11}	S_2
1.7	2.7	1.2	1.3	1.7	1.8	2.7	1.6	0.7	0.4	0.8	0.4

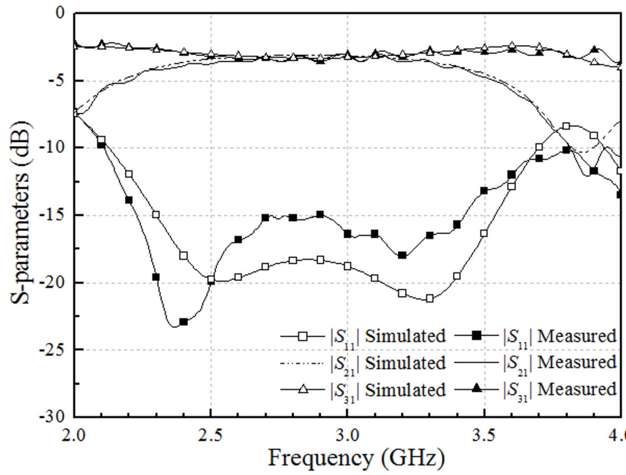

FIGURE 12. The comparison between the simulated and measured $|S_{11}|$, $|S_{21}|$, and $|S_{31}|$ of the proposed balun.

provided by the commercial EM simulator, HFSS, and their final values are tabulated in Table 2. A 33-Ω resistor is selected to improve output isolation and to contribute to transformation of complex impedances. The circuit was fabricated on a 0.762-mm-thick Arlon 25N substrate with a dielectric constant of 3.38 and a loss tangent of 0.0027, and its layout is displayed in Fig. 11. The dimensions of the circuit are listed in Table 3, where the same subscript is adopted for the symbols representing the width and the length of each transmission line.

To conduct standard measurements for the proposed design via a network analyzer, the inherent complex impedances at the input and output ports must be transformed to the 50-Ω system impedance. The following are the design formulas for the complex impedance transformer, which can convert a complex impedance Z_1 to Z_2 [19].

$$Z_1 = R_1 + jX_1, \tag{12a}$$

$$Z_2 = R_2 + jX_2, \tag{12b}$$

$$Z_T = \sqrt{\frac{R_1|Z_2|^2 - R_2|Z_1|^2}{R_2 - R_1}}, \tag{12c}$$

$$\theta_T = \tan^{-1}\left(\frac{Z_T(R_2 - R_1)}{R_2X_1 + R_1X_2}\right), \tag{12d}$$

where Z_T and θ_T are the characteristic impedance and electrical length of the transformer, respectively. The input impedance of $35 - j10$ Ω requires a line of 37.64 Ω in impedance and 48.47° in length for the conversion. A line

TABLE 4. The comparisons on the performance of the proposed design and the baluns from published studies.

Ref.	f_0 (GHz)	$\|S_{21}\|$ (dB)	$\|S_{31}\|$ (dB)	$\angle S_{31}-\angle S_{21}$ (°)	Isolation (dB)	Impedance transformation (Z_L/Z_S) Ω	Bandwidth (phase imbalance)	Bandwidth ($\|S_{11}\|$)	Bandwidth (amplitude imbalance)
[3]	2	−3.45	−3.08	−176.1	−22.5	60+*j*10/35–*j*10	9.8% (±10°)	9.8% (<–13 dB)	9.8% (±1 dB)
[6]	2.45	−3.82	−3.62	179.57	No such function	No such function	Not provided	20.41% (<–10 dB)	Not provided
[12]	1.39	−3.5 ~ −4	−3.5 ~ −4	−183	No such function	No such function	Not provided	96% (<–10 dB)	96.9% (<1 dB)
[13]	2.4	−3.8	−3.8	179	−18	No such function	64% (±5°)	64% (<–10 dB)	Not provided
[15]	1.5	−3.5	−3.5	−177.5	No such function	No such function	Not provided	83.3% (<–10 dB)	Not provided
[16]	2.45	−3.6	−3.4	176	No such function	No such function	36.7% (±6°)	Not provided	36.7% (< 0.5 dB)
This work	**2.8**	**−3.21**	**−3.28**	**180.2**	**−14.2**	**60+*j*10/35–*j*10**	**56% (±5°)**	**67.9% (<–10 dB)**	**35% (< 1 dB)**

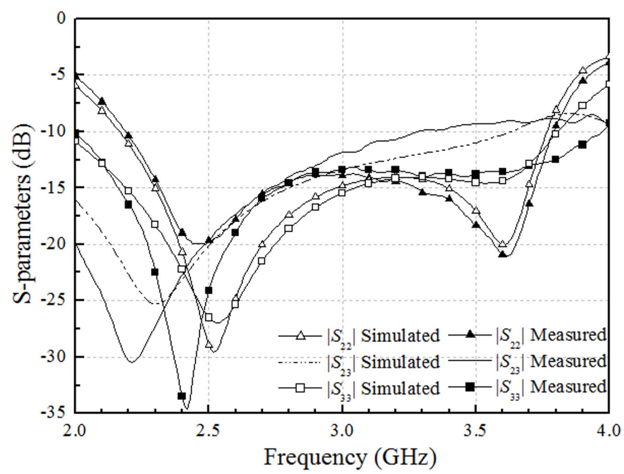

FIGURE 13. The comparison between the simulated and measured $|S_{22}|$, $|S_{23}|$, and $|S_{33}|$ of the proposed balun.

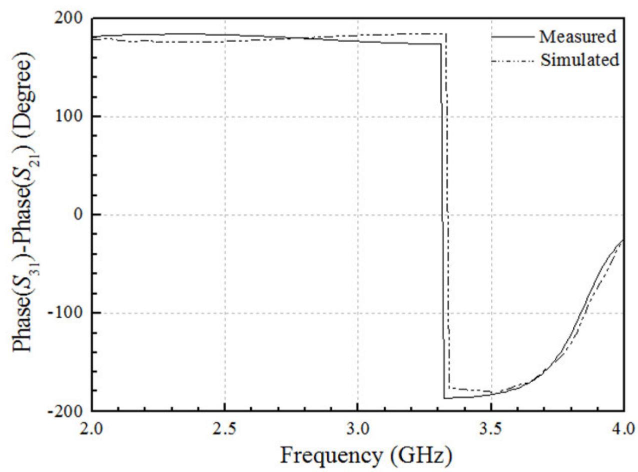

FIGURE 14. The comparison between the simulated and measured $\angle S_{31}-\angle S_{21}$

characterized by an impedance of 59.16 Ω and a length of 49.8° would serve to transform the load impedance of $60+j10$ Ω into $50-\Omega$ system impedance. These impedance transformers are included in Fig. 11 and directly connected to the input/output ports for measurements.

Fig. 12 shows the simulated and measured $|S_{11}|$, $|S_{21}|$, and $|S_{31}|$ of the proposed design. The transmission curves show great consistency between the simulation results and measurement data. The measured bandwidth under the criterion of $(|S_{31}|-|S_{21}|) < 1$ dB ranges from 2.34 to 3.34 GHz, which amounts to a fractional bandwidth of 35%. The values of $|S_{21}|$ and $|S_{31}|$ at 2.8 GHz are −3.21 and −3.28 dB, respectively. The measured bandwidth of $|S_{11}|$ less than −10 dB extends from 2.1 to 4 GHz, which is equivalent to a fractional bandwidth of 67.9%.

Fig. 13 shows that the measured return loss at the output ports match well with their simulated counterparts. The maximum value of the measured isolation is −30.5 dB and occurs at 2.2 GHz. The measured $|S_{11}|$ $|S_{22}|$, $|S_{33}|$, and $|S_{23}|$ are better than −14.2 dB, at 2.8 GHz, which indicates the performance of complex impedance transformation and high isolation.

Fig. 14 further compares the measured and simulated phase differences between the two output signals. As can be seen from the figure, the two curves are in great agreement throughout the entire frequency range of this study. The bandwidth of $\angle S_{31} - \angle S_{21}$ within the range of 180°±5° extends from 2.0 to 3.56 GHz, which is equal to a fractional bandwidth of 56%. The value of the phase difference at 2.8 GHz is 180.2°.

If all three conditions of $|S_{11}| < -10$ dB, $(\angle S_{31} - \angle S_{21}) < 180°\pm5°$, and $(|S_{31}| - |S_{21}|) < 1$ dB are satisfied simultaneously, then the operating bandwidth ranges from 2.34 to 3.34 GHz (or 35%), which is useful

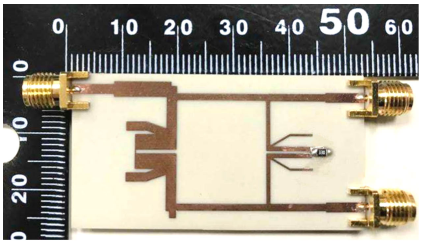

FIGURE 15. Photograph of the fabricated balun.

for wideband applications. Note that the measured results include the effect of the impedance transformation conducted at the input and output ports for measurements. The actual results would have been better without these impedance transformers.

The fabricated circuit of the proposed design is displayed in Fig. 15. The circuit exhibits a small size of $0.35\times0.78\ \lambda_g^2$ with the impedance transformers included for measurements, and λ_g is the guided wavelength at 2.8 GHz. Table 4 compares the performance of the proposed design and the baluns from published studies. As indicated, this design demonstrates superior performance on transformation of complex impedances, high isolation, and wide bandwidth.

IV. CONCLUSION

This paper presents a broadband balun with superior performance on complex impedance transformation and isolation. The proposed design is a 2.8-GHz balun constructed by DSCLs to achieve the goals of wide bandwidth, and transformation of complex source and load impedances. The differential characteristics are established by suppressing the even-mode operation, but exciting the odd-mode operation of a branch-line coupler. An isolation resistor is added to the DSCL between the output ports to improve isolation and to contribute to impedance transformation. A measured wide bandwidth of 35% is obtained under the criterions of $|S_{11}| < -10$ dB, $(\angle S_{31} - \angle S_{21}) < 180°\pm5°$, and $(|S_{31}| - |S_{21}|) < 1$ dB.

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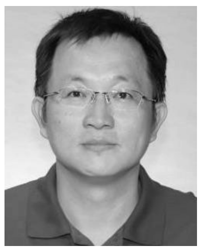

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