UNEQUAL TERMINATION BRANCH-LINE BALUN WITH HIGH-ISOLATION WIDEBAND CHARACTERISTICS

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ABSTRACT: *This article presents a design of an unequal termination impedance branch-line balun with wideband high isolation. The wideband and high isolation characteristics are obtained only in the under-matched region. For an experimental verification, the proposed balun was designed at a center frequency* (f_0) *of 2.6 GHz. The measured results are in good agreement with the simulations. From the measurement, the power divisions are −3.29 dB and −3.3 dB. The return loss at* f_0 *is 22.3 dB and is higher than 20 dB over a bandwidth of 0.51 GHz. The isolation between output ports is higher than 19 dB for the bandwidth of 0.64 GHz. The phase imbalance between two output ports is 180° ± 5° for the bandwidth of 0.64 GHz.* © 2016 Wiley Periodicals, Inc. Microwave Opt Technol Lett 58:1775–1778, 2016; View this article online at wileyonlinelibrary.com. DOI 10.1002/mop.29914

Key words: *branch-line balun; coupled line; isolation circuit; unequal termination impedance; wideband*

1. INTRODUCTION

A branch-line balun is a three-port device that can be analyzed as a four-port symmetrical network by the termination of one port as open [1] and without an isolation circuit between the output ports. As the balun has been used for various applications such as push–pull amplifiers, antennas, and mixers, the high isolation between output ports is one of its important design issues.

Branch-line baluns have been widely investigated in other recent works [2–6]. In Refs. 2,3, the branch-line balun with stubs on its vertical branches could eliminate an unwanted even-mode signal and reduce the total circuit size. However, the circuit performances had relatively narrow bandwidths and did not consider the isolation between output ports. In Ref. 4, the bandwidth was enhanced by attaching a short-circuited quarter-wavelength stub to the output junction ports of the branch line. Similarly, a wideband balun using artificial fractal-shaped composite right/left handed transmission lines (TLs) was reported in Ref. 5. However, these two works also did not consider the isolation characteristics between the output ports. In Ref. 6, the bandwidth was enhanced by choosing an appropriate matched region. Moreover, a high isolation could be obtained by adding a resistor and a coupled line between the output balanced ports. However, the circuit size was large due to the added coupled line and a resistance.

In this article, a branch-line balun structure is proposed by modifying the isolation circuit. The proposed balun can provide wideband, high isolation, size reduction, and can be designed with unequal termination impedance.

2. ANALYSIS

Figure 1 shows the proposed circuit of the branch-line balun with wideband high isolation circuit. Two open-circuited coupled lines connected back-to-back are used for the wideband isolation. The resistor R is connected at the center of the coupled lines for the high isolation characteristic.

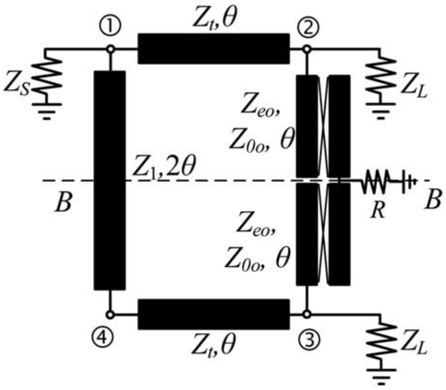

Figure 1 Block diagram of proposed unequal termination branch-line balun

From Ref. 6, the even- and odd-mode excitations can be used to analyze the proposed circuit. The input reflection coefficient (S_{11}) is equal to the odd-mode reflection coefficient ($S_{11\mathrm{o}}$). Under the odd-mode excitation as shown in Figure 2(a), the resistor R does not have any effect on the circuit operation. The odd-mode reflection and transmission coefficients are derived as Eq. (1a) from the *ABCD*-parameters.

$$S_{11\mathrm{o}}=\frac{A_\mathrm{o}Z_L+B_\mathrm{o}-CrZ_L^2-D_\mathrm{o}rZ_L}{A_\mathrm{o}Z_L+B_\mathrm{o}+CrZ_L^2+D_\mathrm{o}rZ_L} \tag{1a}$$

$$S_{21\mathrm{o}}=\frac{2Z_L\sqrt{r}}{A_\mathrm{o}Z_L+B_\mathrm{o}+CrZ_L^2+D_\mathrm{o}rZ_L} \tag{1b}$$

where

$$A_\mathrm{o}=\cos\theta\left\{1+\left[NZ_t\sin\theta/\left(M-N^2\cos^2\theta\right)\right]\right\} \tag{2a}$$

$$B_\mathrm{o}=jZ_t\sin\theta \tag{2b}$$

$$C_\mathrm{o}=j\sin\theta\left[\frac{1}{Z_t}-\frac{1}{Z_t\tan^2\theta}-\frac{Z_tN\cos^2\theta}{Z_1(M-N^2\cos^2\theta)}-\frac{N\cos^2\theta}{M-N^2\cos^2\theta}\right] \tag{2c}$$

$$D_\mathrm{o}=\cos\theta[1+(Z_t/Z_1)] \tag{2d}$$

$$M=(Z_{0\mathrm{e}}-Z_{0\mathrm{o}})^2/4 \tag{2e}$$

$$N=(Z_{0\mathrm{e}}+Z_{0\mathrm{o}})/2 \tag{2f}$$

$Z_{0\mathrm{e}}$ and $Z_{0\mathrm{o}}$ are the even- and odd-mode impedances of the coupled line, respectively, and r is the impedance transforming ratio. The related balun condition $r = 2Z_S/Z_L$ should be satisfied at the odd-mode excitation [3]. At f_0, $S_{11\mathrm{o}}$ is obtained as Eq. (3).

$$S_{11\mathrm{o}}\big|_{f_0}=\frac{Z_t^2-rZ_L^2}{Z_t^2+rZ_L^2} \tag{3}$$

From Eq. (3), three different matched regions can be categorized [6]. The perfect matched region is obtained when $S_{11\mathrm{o}}|_{f0}$ is equal to zero. Under this matched region, the characteristic impedance Z_t of horizontal TLs can be derived as Eq. (4).

$$Z_t=Z_L\sqrt{r} \tag{4}$$

For the over-matched region ($Z_t > Z_L\ r^{0.5}$) with the specific $S_{11\mathrm{o}}|_{f0}$, Z_t can be calculated as Eq. (5) by using Eq. (3).

$$Z_t=Z_L\sqrt{\frac{r\left(1+S_{11\mathrm{o}}|_{f_0}\right)}{1-S_{11\mathrm{o}}|_{f_0}}} \tag{5}$$

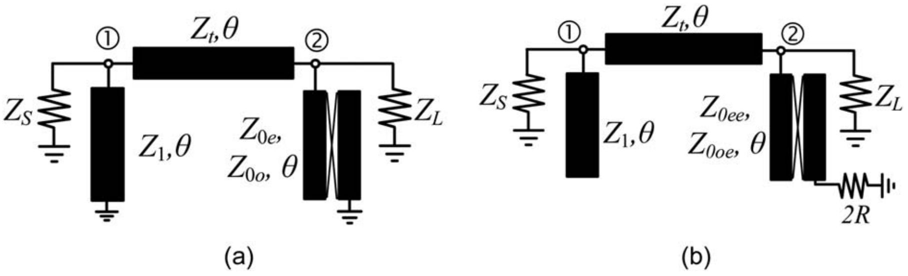

Figure 2 Equivalent circuit of proposed structure: (a) odd-mode and (b) even-mode excitations

Similarly, for the under-matched region ($Z_t < Z_L\ r^{0.5}$) with the specific $S_{11o}|_{f0}$, Z_t can be found as Eq. (6).

$$Z_t = Z_L\sqrt{\frac{r\left(1-S_{11o}|_{f_0}\right)}{1+S_{11o}|_{f_0}}} \tag{6}$$

Moreover, the even-mode impedance (Z_{0e}) of the coupled line can be calculated to provide transmission poles (TPs) in the passband [6]. From Eq. (1a), Z_{0e} can be derived as Eq. (7) by setting $S_{11o} = 0$ in Eq. (1a).

$$Z_{0e} = \frac{(2Z_{0o}+p) \mp \sqrt{p(8Z_{0o}+p)}}{2} \tag{7}$$

where

$$p = \frac{2Z_1Z_t}{(Z_1+Z_t)r - Z_1}. \tag{8}$$

And because Z_{0e} must be larger than Z_{0o}, the negative sign in Eq. (7) must be avoided. From Eq. (1a), the normalized TP frequencies in the under-matched region can be found as Eq. (9).

$$\frac{f_p}{f_0} = \frac{2\cos^{-1}\sqrt{x}}{\pi} \tag{9}$$

where

$$x = \frac{-a_2 \pm \sqrt{a_2^2 - 4a_1a_3}}{2a_1} \tag{10a}$$

$$a_1 = \left[Z_t^2 Z_1 N - (Z_1+Z_t)(N+Z_t) r Z_L^2\right] N \tag{10b}$$

$$a_2 = \left[\left(rZ_L^2 - Z_t^2\right)Z_1\left(M+N^2\right) + rZ_L^2 Z_t(M+Z_tN+NZ_1)\right] \tag{10c}$$

$$a_3 = \left(Z_t^2 - rZ_L^2\right)Z_1 M \tag{10d}$$

TABLE 1 Calculated Element Values of Balun With Different Matched Regions

Matched regions	$Z_{0o}=80\,\Omega$, $S_{11o}\vert_{f0}=S_{23}\vert_{f_0}=-20\,\text{dB}$, $Z_L=25\,\Omega$, $r=4$, $Z_1=60\,\Omega$		
	z_t (Ω)	Z_{0e} (Ω)	R (Ω)
Perfect	50	138.77	17.27
Under	45.23	137.14	13.36
Over	55.28	140.37	22.27

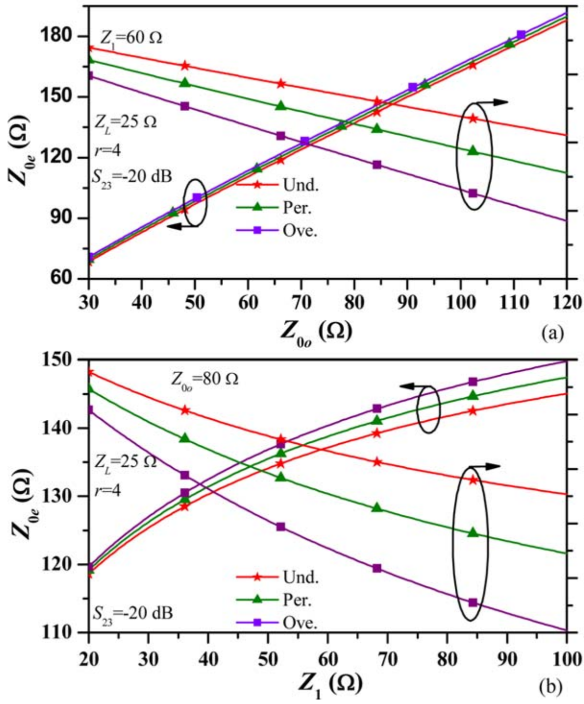

Figure 3 Variation of Z_{0e} and R according to: (a) Z_{0o} and (b) Z_1. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

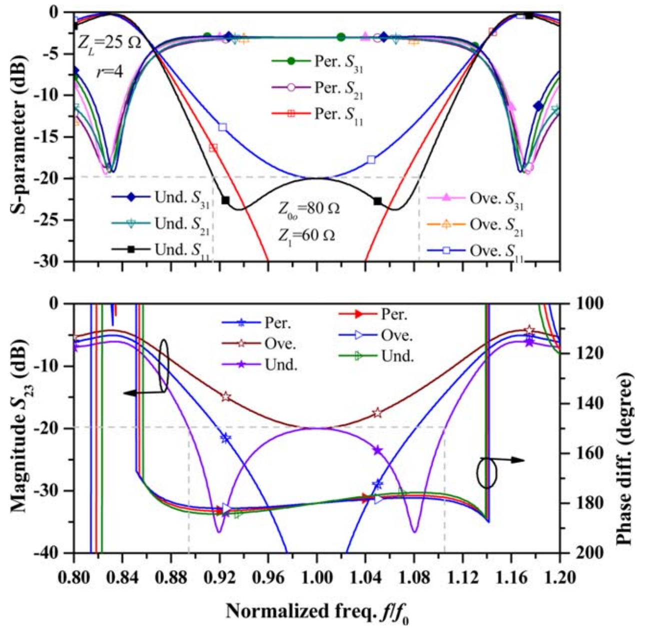

Figure 4 Freqency responses of proposed balun for different matched regions. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

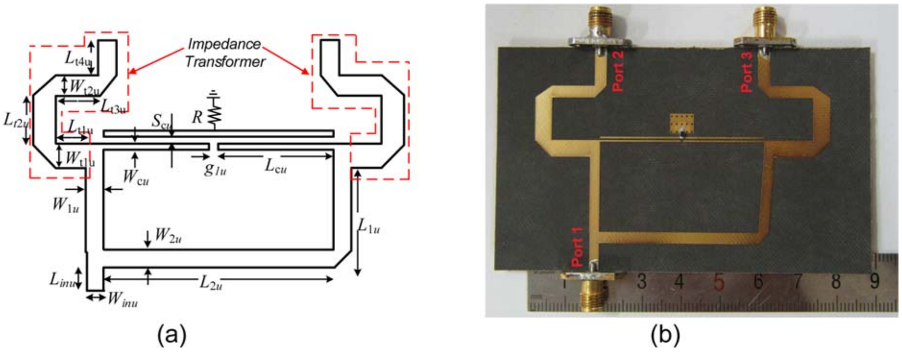

Figure 5 (a) Layout of proposed balun and (b) photograph of fabricated PCB. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

TABLE 2 Physical Dimensions and Component Value of Fabricated PCB (unit: mm)

$W_{1u} = 2.5$	$L_{2u} = 40.61$	$S_{cu} = 0.45$	$g_{1u} = 0.6$	$L_{t2u} = 11$	$L_{t4u} = 10$
$L_{1u} = 19$	$W_{inu} = 2.4$	$W_{cu} = 0.4$	$W_{t1u} = 4.3$	$W_{t2u} = 3.07$	$R = 16\ \Omega$
$W_{2u} = 2.8$	$L_{inu} = 7$	$L_{cu} = 20.7$	$L_{t1u} = 10$	$L_{t3u} = 11$	

For the even-mode excitation, the resistor R is split in half along the axis-BB' and its resistance is doubled, as shown in Figure 2(b). The high isolation can be obtained due to this resistor R.

For the perfect matched region, the resistance R is given as Eq. (11).

$$R = \frac{rZ_L(Z_{0e} - Z_{0o})^2}{8Z_t^2} \tag{11}$$

For the over-matched region with the specific isolation $S_{23}|_{f0}$, the resistance R can be derived as Eq. (12).

$$R = \frac{\left[S_{23}|_{f_0}\left(Z_t^2 + rZ_L^2\right) + rZ_L^2\right](Z_{0e} - Z_{0o})^2}{8Z_L\left[Z_t^2 - \left(Z_t^2 + rZ_L^2\right)S_{23}|_{f_0}\right]} \tag{12}$$

where S_{23} can be derived from S_{22e} and S_{22o} [7].

Similarly, for the under-matched region with the specific isolation $S_{23}|_{f0}$, the resistance R can be found as Eq. (13).

$$R = \frac{(Z_{0e} - Z_{0o})^2\left[rZ_L^2 - S_{23}|_{f_0}\left(Z_t^2 + rZ_L^2\right)\right]}{Z_L 8\left[S_{23}|_{f_0}\left(Z_t^2 + rZ_L^2\right) + Z_t^2\right]} \tag{13}$$

Figure 3 shows variations of Z_{0e} and R according to Z_{0o} and Z_1 for different matched regions. As Z_1 and Z_{0o} increase, Z_{0e} and R are gradually increased. Z_t and R should be calculated with the same matched region to obtain design specifications (e.g., if the under-matched Z_t is chosen, then R must also be chosen at the under-matched region).

To illustrate the design equations, the unequal termination impedance balun is designed with specifying $S_{11o}|_{f0} = S_{23}|_{f0} = -20$ dB, $Z_{0o} = 80\ \Omega$, $Z_1 = 60\ \Omega$, $r = 4$, and $Z_L = 25\ \Omega$. The magnitudes of $S_{11o}|_{f0}$ and $S_{23}|_{f0}$ can be chosen differently according to design specifications.

The calculated element values are listed in Table 1 for different matched regions. From Table 1, the frequency responses are shown in Figure 4. As seen in this figure, $S_{11o}|_{f0}$ and $S_{23o}|_{f0}$ are exactly -20 dB in the cases of the under-matched and over-matched regions. The phase different is obtained 180° at the

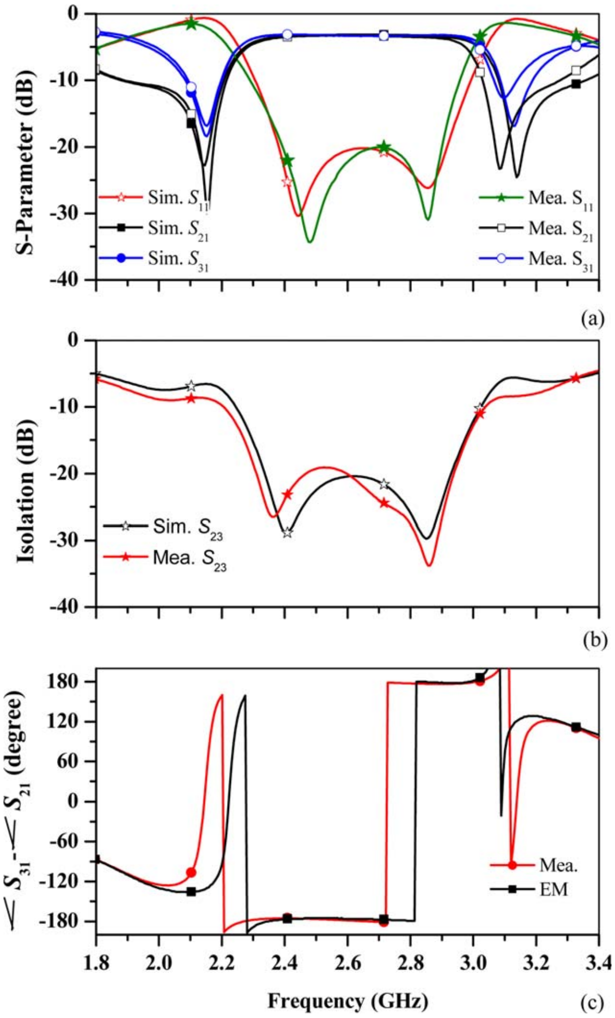

Figure 6 Simulation and measurement results of proposed balun (a) S-parameter, (b) Isolation, and (c) phase impedance. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

TABLE 3 Performance Comparison With Previous Works

	This work	[1]	[2]	[3]	[4]	[5]	[6]
f_0 (GHz)	2.6	2.4	1	1	1.5	1.5	2.6
Ter. Imp. (Ω)	50–25	50	50	50	50	50	50
FBW (%)	20*	9.2†	13*	17*	35*	54*	20.76
Phase diff.	180° ± 5°	180 °± 1°	180 °± 5°	180° ± 5°	180° ± 10°	180° ± 3.4°	180° ± 5°
Isolation (dB)	19 (FBW=24.6%)	NA	NA	NA	NA	NA	18 (FBW=28%)
Circuit size (mm^2)	35 × 55	NA	NA	NA	15.9 × 15.9	29 × 30.5	60 × 60

*−19 dB S11 FBW.
†−12.2 dB S_{11} FBW, Ter. Imp.: termination impedance.

center frequency (f_o). Moreover, the wideband characteristic is found in the under-matched region compared to the perfect and over-matched regions.

The design steps of the proposed balun are as follows.

a. First, specify Z_{0o}, Z_1, f_0, Z_L, Z_S, $S_{23}|_{f0}$, and $S_{11o}|_{f0}$ for all matched regions.
b. For the perfect matched region, calculate Z_t using Eq. (4). Then calculate Z_{0e} and R using Eqs. (7) and (11), respectively.
c. For the over-matched region, calculate Z_t using Eq. (5). Then calculate Z_{0e} and R using Eqs. (7) and (12), respectively.
d. For the under-matched region, calculate Z_t using Eq. (6). Then calculate Z_{0e} and R using Eqs. (7) and (13), respectively.
e. Finally, obtain the physical dimensions of the coupled lines according to PCB substrate from RF circuit simulator and optimize using electromagnetic (EM) simulator.

3. SIMULATION AND MEASUREMENT RESULTS

To demonstrate and validate the analysis, the branch-line balun was designed at an f_o of 2.6 GHz. The designed values of $S_{11o}|_{f0}$ and $S_{23}|_{f0}$ are −20 dB with 50–25 Ω termination impedances. The under-matched region was chosen for wideband characteristics. The circuit was fabricated on RT/Duroid 5880 substrate with $\varepsilon_r = 2.2$ and h = 31 mils. EM simulation was performed using ANSYS HFSS v15.

Figure 5 shows the EM simulation layout and a photograph of the fabricated balun. The circuit size is 35 ×× 55 mm^2 ignoring the impedance transformer to match with 50 Ω for the measurement. The physical dimensions and component value are shown in Table 2.

Figure 6 shows the simulation and measurement results of the fabricated balun. From the measurement, the return loss is obtained as 22.3 dB at f_0. The bandwidth of 20 dB return loss is 0.51 GHz (2.39–2.9 GHz). The measured results are in good agreement with the simulations. The measured power divisions are −3.29 dB and −3.3 dB at f_0, respectively. The amplitude division of −3 ± 0.6 dB is obtained within the bandwidth of 0.51 GHz. The isolation between the output ports is obtained as 20.05 dB at f_0. Isolation higher than 19 dB is obtained over a bandwidth of 0.64 GHz (2.3–2.94 GHz). The measured phase imbalance between two output ports is 180° ± 5° over the bandwidth of 0.64 GHz. The performance comparisons are summarized in Table 3.

The proposed balun provided wideband and high isolation characteristics with unequal termination impedance. The circuit size of the proposed work is much improved when compared with Ref. 6.

4. CONCLUSION

In this article, a branch-line balun was proposed. Shunt coupled lines with a resistor between the output ports were used to obtain wideband and high isolation characteristics. The measurement results are in good agreement with simulation results. The proposed structure is simple to design and fabricate and is applicable for wideband RF systems.

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UNCONDITIONALLY STABLE FDTD SCATTERED FIELD FORMULATION FOR DISPERSIVE MEDIA

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ABSTRACT: *A new unconditionally stable scattered field (SF) formulation for the finite difference time domain (FDTD) technique applied to dispersive media is presented. The scheme is based on alternating direction implicit (ADI) principle but, unlike ADI, it does not require computation and storage of field values at the intermediate time steps which reduces computational costs and memory. Dispersive media characterized by Debye and Lorentz models are incorporated in the proposed SF FDTD scheme by auxiliary differential equation (ADE) method. For each of the dispersive media unconditional stability and accuracy of the scheme are validated by numerical tests. The scheme can perform faster*