A Dual-Band Balun Using Partially Coupled Stepped-Impedance Coupled-Line Resonators

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***Abstract*—In this paper, a recently proposed dual-band resonator structure consisting of a pair of partially coupled stepped-impedance lines is theoretically investigated. The new resonator configuration contains a number of attractive features for dual-band applications. A new type of dual-band balun that is constructed using a pair of such coupled stepped-impedance resonators is fully studied both theoretically and experimentally. Design equations for the balun are derived by an even- and odd-mode approach. A prototype of such dual-band balun operating at 900 MHz and 1.8 GHz is designed, fabricated, and measured. Good agreement between the designed and measured responses proves the concept of the dual-band balun and validates the design formulas.**

***Index Terms*—Baluns, coupled lines, dual-band baluns, stepped-impedance resonators (SIRs).**

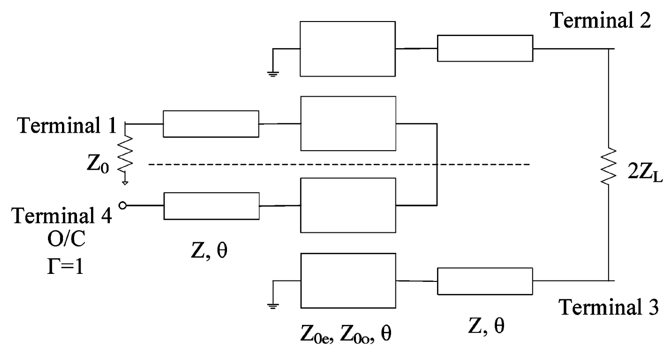

Fig. 1. Schematic of the proposed dual-band balun using partially coupled stepped-impedance lines.

I. Introduction

THE NEED for dual-band components grows rapidly with the ever-increasing demand for dual-band and multiband wireless terminal products, including mobile phones, wireless adapters and routers, and laptops that support multiband wireless local area networks (WLANs), etc. There are many ways to design a dual-band component. A popular and obvious option is to use the stepped-impedance approach [1]. Many people employ this technique mainly for resonator size reduction. Some have generalized this technique and used multiple stepped-impedance sections to further miniaturize a single-section stepped-impedance resonator (SIR) [2]. In view of dual-band applications, the stepped-impedance technique has been employed in filter [3]–[5] and power divider [6] designs.

A balun is a key component in microwave and RF circuits such as a balanced mixer, a frequency multiplier, and an antenna feed network. Many distributed and lumped balun configurations have been proposed for different applications [7]–[10]. Distributed baluns consist of multiple sections of coupled lines or transmission lines. Lumped-element baluns also find their uses in many applications due to their relatively small size advantage. Apart from these two types, baluns employing both lumped as well as distributed elements have also been reported. Among various configurations, the Marchand balun is the most popular choice [11].

While most research focuses on balun size reduction issues, very little literature is concerned with dual-band designs [12]–[14]. In [12], a method based on the lumped-element equivalent circuit of a quarter-wave transformer was used. The slopes of the magnitudes of S_{21} and S_{31} at the operating frequencies of this dual-band balun are inherently with opposite signs. Therefore, the bandwidth with a reasonable amplitude balance requirement is very narrow. In [13], a dual-band *LC*-type balun was proposed. In [14], a coaxial sleeve-like dual-band balun was proposed for decreasing the influence of RF feed cables in small antenna measurements. A balun using a stepped-impedance technique for single frequency-band applications is reported in [15].

Recently, a new component configuration, called partially coupled stepped-impedance coupled-line resonators, was proposed by the authors for constructing a dual-band balun filter [16] in which the focus was on the design equations for a balun filter. The basic properties of the partially coupled stepped-impedance coupled-line resonators will be studied in depth in this paper. After a thorough mathematical investigation of its dual-band properties, it is found that this resonator configuration has a number of attractive features for dual-band applications, which are: 1) a dual-band property with a large dual-band frequency ratio (f_2/f_1); 2) multiple coupling choices for alleviating manufacturing constrains; and 3) simple design formulas, as this component configuration only requires the control of one coupling section. As an example, in the novel dual-band Marchand balun shown in Fig. 1, the line impedances of the coupled sections depend on the ratio of the two

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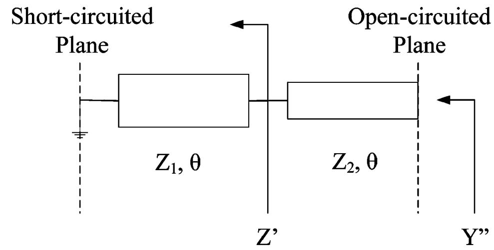


Fig. 2. Schematic of a $\lambda/4$ SIR.

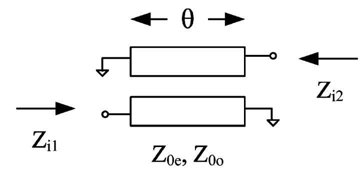


Fig. 3. Schematic of a conventional coupled-line section with diagonally shorted ends.

operating frequencies, as well as the manufacturing constrains. Design formulas of the balun are derived by employing an even- and odd-mode analysis. A prototype of the proposed new dual-band balun operating at 900 MHz and 1.8 GHz is designed and fabricated on an FR4 substrate. Good agreement between designed and measured responses proves the proposed concept and verifies the design equations.

II. Theory

The schematic of the proposed dual-band balun is shown in Fig. 1. The circuit can be considered as a symmetrical four-port network having one of its ports terminated by a short or open circuit. In order to have this balun operating at two desired frequencies of f_1 and f_2, the values of Z, Z_{0e}, Z_{0o}, and θ should be correctly designed. For simplicity, we assume that $Z_0 = Z_L = 50\ \Omega$ and all transmission line sections have the same electrical length θ. In addition, the characteristic impedances of those uncoupled transmission lines are all equal to Z.

The analysis for this balun can be divided into three sections. Firstly, the dual-band behavior of a $\lambda/4$ SIR is considered. Secondly, seven possible resonator configurations using the concept of partially coupled stepped-impedance coupled lines are discussed. Finally, characteristics and a design procedure for the proposed dual-band balun are provided.

A. $\lambda/4$ SIRs

Fig. 2 shows the schematic of a $\lambda/4$ SIR. Under the resonant condition, Y'' should be equal to zero [1]. Thus,

$$Y'' = \frac{Z_2 - Z_1 \tan^2\theta}{jZ_2(Z_1+Z_2)\tan\theta} = 0 \tag{1a}$$

where

$$\theta = \tan^{-1}\sqrt{R_z} \tag{1b}$$
$$R_z = Z_2/Z_1. \tag{1c}$$

Obviously, the lowest higher order resonant frequency of a $\lambda/4$ SIR satisfies that

$$\tan\theta_{SA} = \tan(\pi-\theta) = -\sqrt{R_z}. \tag{2}$$

From this equation, the first two resonant frequencies f_1 and f_2 can be related to the impedance ratio R_z by

$$\frac{f_2}{f_1} = \frac{\theta_{SA}}{\theta} = \frac{\pi - \tan^{-1}\sqrt{R_z}}{\tan^{-1}\sqrt{R_z}} = \frac{\pi}{\tan^{-1}\sqrt{R_z}} - 1. \tag{3}$$

Therefore, given two desired resonant frequencies, the length and impedance ratio of a $\lambda/4$ SIR can be obtained by (1b) and (3), respectively. A $\lambda/4$ SIR only refers that the zero admittance condition (1a) for a shorted SIR is held for both f_1 and f_2. However, the electric length θ is referred to f_1. The other parameters that remain to be determined are Z, Z_{0e}, and Z_{0o}. Notice that $Z = R_z\sqrt{Z_{0e}Z_{0o}}$ [17].

B. Partially Coupled Stepped-Impedance Coupled Lines

For a pair of partially coupled stepped-impedance coupled lines, an $ABCD$ matrix can be used to reveal its dual-band properties. For comparative purposes, a pair of conventional coupled lines with diagonally shorted ends is depicted in Fig. 3. The counterpart configuration using the partially coupled stepped-impedance coupled lines is shown in Fig. 4(a).

There are seven possible circuit topologies for dual-band applications, as listed in Fig. 4, using a pair of partially coupled stepped-impedance coupled lines. It is straightforward to derive the two-port network matrix for each of these topologies.

C. Dual-Band Baluns

When a balun is considered as a three-port device (ports 1–3 in Fig. 1 are defined by terminals 1–3, respectively), the following two conditions should be theoretically satisfied:

$$S_{21} = -S_{31} \tag{4a}$$
$$S_{11} = 0 \tag{4b}$$

which serve as the basis for deriving the design equations for the proposed balun. As observed from Fig. 1, the balun schematic can be viewed as a four-port symmetrical network with a load, whose reflection coefficient looking from the balun to the load is Γ at terminal 4.

Being symmetrical, the four-port network can be characterized by using the even- and odd-mode analysis with the corresponding circuits shown in Fig. 5.

In order to satisfy (4), it is straightforward to derive the following two equations [18]:

$$\frac{T_{\text{even}}(1-\Gamma_{\text{odd}}\Gamma)}{2-\Gamma(\Gamma_{\text{even}}+\Gamma_{\text{odd}})} = 0 \tag{5a}$$
$$\frac{\Gamma_{\text{even}}+\Gamma_{\text{odd}}-2\Gamma_{\text{even}}\Gamma_{\text{odd}}\Gamma}{2-\Gamma(\Gamma_{\text{even}}+\Gamma_{\text{odd}})} = 0. \tag{5b}$$

For the case of the open circuit ($\Gamma = 1$) at terminal 4, (5) can be rewritten as

$$T_{\text{even}} = 0 \tag{6a}$$
$$Z_{\text{even}} + Z_{\text{odd}} = 2Z_0. \tag{6b}$$

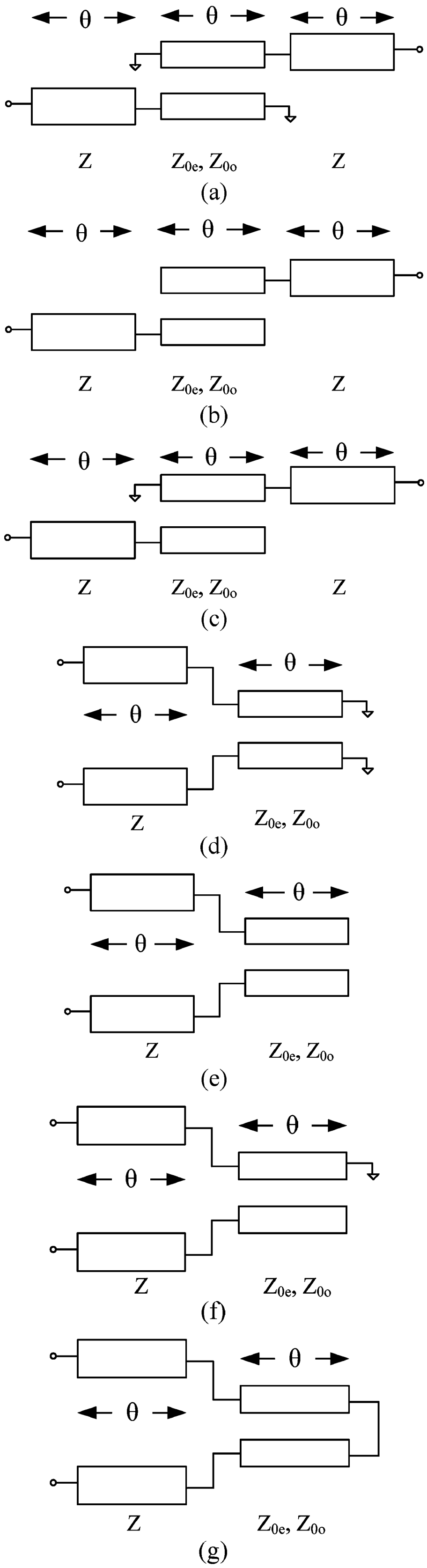


Fig. 4. Seven possible configurations of partially coupled stepped-impedance lines for dual-band applications.

Equation (6a) is automatically satisfied as the even-mode circuit is an all-stop circuit [19]. On the other hand, (6b) can only be satisfied by appropriately choosing Z, Z_{0e}, and Z_{0o}.

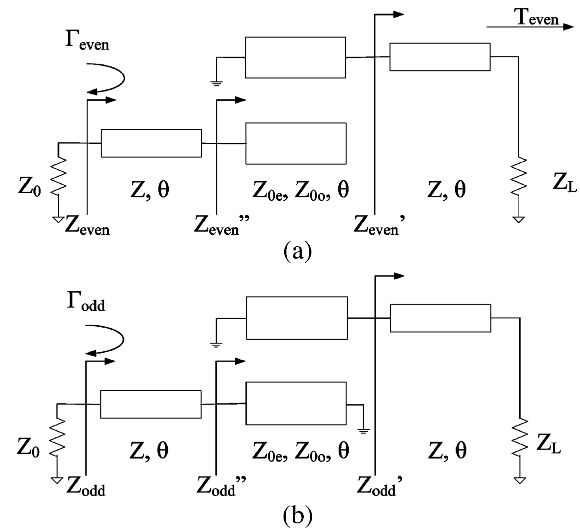


Fig. 5. (a) Even- and (b) odd-mode equivalent circuits of the symmetrical four-port network.

Using the Y-matrix analysis, the even-mode equivalent impedances at the input port can be obtained as

$$Z_{\text{even}} = j\frac{R_z^2\sqrt{Z_{0e}Z_{0o}}(Z_{0e}+Z_{0o})}{2\sqrt{Z_{0e}Z_{0o}}+R_z(Z_{0e}+Z_{0o})}\tan\theta - j\frac{2R_zZ_{0e}Z_{0o}}{2\sqrt{Z_{0e}Z_{0o}}+R_z(Z_{0e}+Z_{0o})}\cot\theta. \quad (7)$$

Similarly, the odd-mode equivalent impedances at the input port can be expressed as

$$Z_{\text{odd}} = \frac{R_z\sqrt{Z_{0e}Z_{0o}}\left(1/Y''_{\text{odd}} + jR_z\sqrt{Z_{0e}Z_{0o}}\tan\theta\right)}{R_z\sqrt{Z_{0e}Z_{0o}} + j\tan\theta/Y''_{\text{odd}}} \quad (8a)$$

where

$$Y''_{\text{odd}} = \frac{(Y_{0o}-Y_{0e})^2\csc^2\theta}{4/Z'_{\text{odd}} - 2j(Y_{0e}+Y_{0o})\cot\theta} - j\frac{Y_{0e}+Y_{0o}}{2}\cot\theta \quad (8b)$$

and

$$Z'_{\text{odd}} = \frac{Z(Z_L + jZ_1\tan\theta)}{Z + jZ_L\tan\theta}. \quad (8c)$$

Here $Z_L = Z_0$. Notice that Z_{even} and Z_{odd} depend only on Z_{0e} and Z_{0o}, as other parameters are already determined by (1) and (3). Substituting (7) and (8a) into (6b), one can find that there is no solution for Z_{0e} and Z_{0o} such that (6b) is exactly satisfied. Nevertheless, one can always find an approximate solution that can sufficiently satisfy the equation. To view the range of a possible approximate solution, it is desirable to define an error function $\text{err} = |Z_{\text{even}} + Z_{\text{odd}} - 2Z_0|$ and plot it against Z_{0e} and Z_{0o}.

Now, suppose we would like to design a balun operating at both 2.4 and 5.8 GHz. According to (1a)–(3), the value of Z is determined by the ratio of these two frequencies with $Z = 1.721\sqrt{Z_{0e}Z_{0o}}$. Thus, a possible approximate solution is to choose a pair of Z_{0e} and Z_{0o} such that the error function is sufficiently small. Fig. 6 shows the contour plot of the error function err against Z_{0e} and Z_{0o}, and obviously there is no

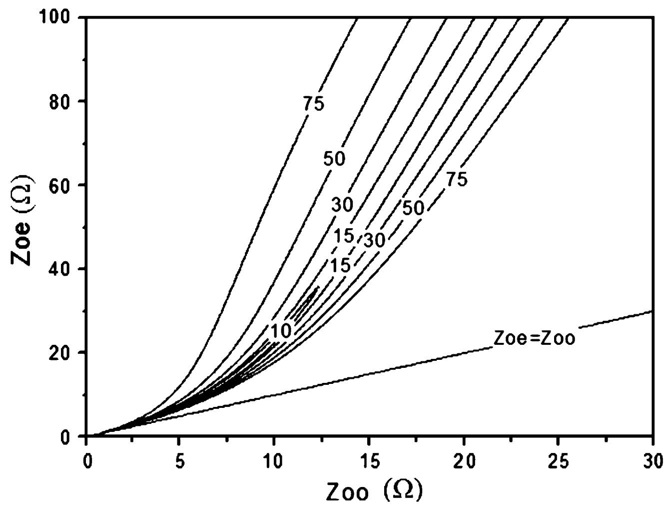


Fig. 6. Contour plot of the error function $\mathrm{err}\,(Z_{0e}, Z_{0o})$ for a dual-band balun operating at 2.4 and 5.8 GHz.

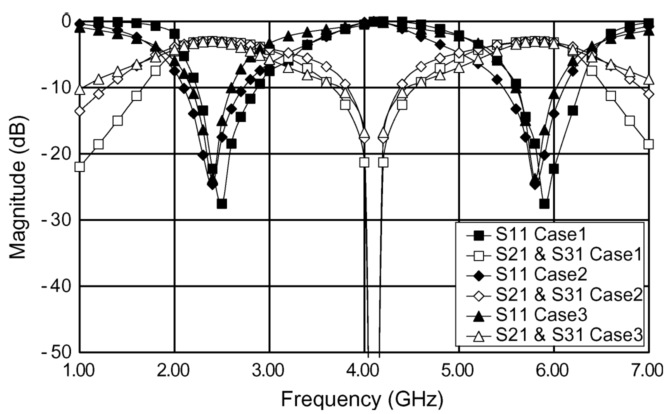


Fig. 7. Magnitude responses of a dual-band balun for three different approximate solutions. Case 1: $Z_{0e} = 23.1\ \Omega$ and $Z_{0o} = 10.0\ \Omega$. Case 2: $Z_{0e} = 54.0\ \Omega$ and $Z_{0o} = 15.0\ \Omega$. Case 3: $Z_{0e} = 91.3\ \Omega$ and $Z_{0o} = 20.0\ \Omega$.

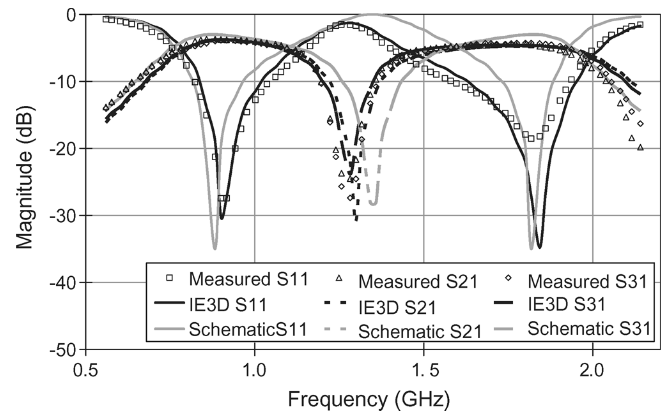


Fig. 8. Comparison of the results of the EM designed, measured, and schematic circuit.

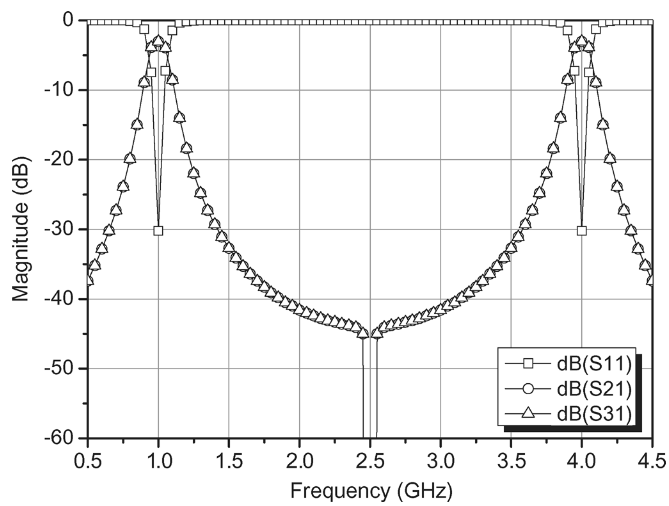


Fig. 9. Magnitude response of a dual-band balun operating at 1- and 4-GHz bands.

exact solution for $\mathrm{err} = 0$. Notice that only the region with $Z_{0e} > Z_{0o}$ is valid.

Given three different approximate solutions for the example balun design: 1) $Z_{0e} = 23.1\ \Omega$ and $Z_{0o} = 10.0\ \Omega$; 2) $Z_{0e} = 54.0\ \Omega$ and $Z_{0o} = 15.0\ \Omega$; and 3) $Z_{0e} = 91.3\ \Omega$ and $Z_{0o} = 20.0\ \Omega$, three different responses are obtained. Fig. 7 shows the magnitude responses for the above three solutions. Notice that they all give an acceptable balun performance.

The proposed dual-band balun is more favorable to work under the condition of $f_2/f_1 < 3$. This conclusion can be easily understood by considering the following three different cases.

Case 1) $f_2/f_1 < 3$
From (3), one can find that, in this case, $R_z > 1$. That is to say, the coupled section will be the low-impedance portion of the two SIRs. The example whose responses are shown in Fig. 8 falls into this category.

Case 2) $f_2/f_1 = 3$
In this case, $R_z = 1$, and $\theta = \tan^{-1}\sqrt{R_z} = \pi/4$. The coupled stepped-impedance line pair becomes a conventional coupled-line section, as this is essentially a conventional Marchand balun, but with a $\lambda/8$ rather than a $\lambda/4$ long coupled section.

Case 3) $f_2/f_1 > 3$
Consequently, $R_z < 1$ and the coupled section must be the high-impedance portion of the two SIRs. It is worth mentioning that the operating bandwidths are much smaller than those of the cases in which $f_2/f_1 < 3$. For example, if a balun operates at 1 and 4 GHz, it can be found that $R_z = 0.528$ and $\theta = 36^\circ$. Fig. 9 shows the magnitude responses of such a balun with $Z_{0e} = 10.6\ \Omega$ and $Z_{0o} = 8.3\ \Omega$.

III. Design Example

According to the design procedure outlined above, a prototype dual-band balun using stripline-type partially coupled stepped-impedance coupled-line resonators is designed. The balun operates at 900 and 1800 MHz with $Z_0 = Z_L = 50\ \Omega$. Electrical parameters of the balun are $Z_{0e} = 17.48\ \Omega$, $Z_{0o} = 7.81\ \Omega$, $Z = 35.05\ \Omega$, $R_z = 3$, and $\theta = 60^\circ$. Translating these electrical parameters to layout dimensions using a stripline-type format (see Fig. 10) with a substrate thickness

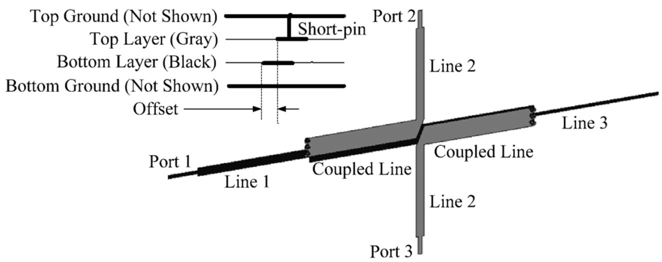
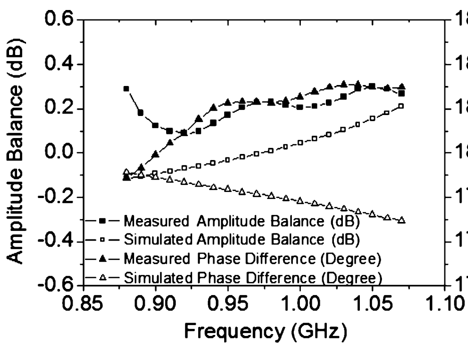
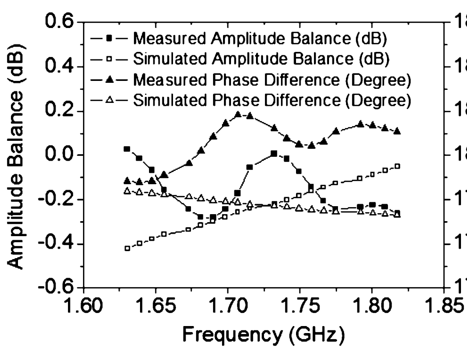


Fig. 10. Layout of the stripline-type dual-band balun (grounds are not shown).



(a)



(b)

Fig. 11. Performances of the prototype dual-band balun at: (a) 900 MHz and (b) 1.8 GHz.

of 2.22 mm, a dielectric constant of 3.9, and a loss tangent of 0.01, the following physical dimensions can be easily obtained:

- *Lines 1 and 2*: Length = 26.40 mm, width = 2.32 mm.
- *Coupled line*: Length = 26.57 mm, width = 5.37 mm, offset = 1.08 mm.
- *Line 3*: Length = 29.45 mm, width = 0.84 mm.

Notice that a three-layer printed circuit board (PCB) is used with thickness of 0.71, 0.80, and 0.71 mm, respectively.

The final layout of the prototype balun is finally tuned using full-wave EM simulation software—IE3D from Zeland Inc., Fremont, CA [20]. Due to the inductive effect of the shorted ends in the coupled-line sections, there is an undesirable slope in the higher frequency passband transmission, which degrades the bandwidth of amplitude balance at the high-frequency band. In addition, the parasitic effects in the circuit structure also affect the center frequencies of the two bands. It is found, in the final electromagnetic (EM) tuning stage, that increasing the characteristic impedance of line 3 can reduce the slope. As a result of adjusting the characteristic impedance, the characteristic impedances and physical lengths also need to be adjusted accordingly in order to have a good in-band matching and flatter transmission. Nevertheless, the physical design is not unique.

The EM designed responses, together with the measured responses, are superposed in Fig. 8, showing an excellent correlation. For illustrative purpose, the responses of the original schematic circuit are also shown in Fig. 8.

Fig. 11(a) and (b) shows the amplitude balance and phase difference of the prototype balun at each operating band. It is seen from the figure that the amplitude balance is less than 0.3 dB and the phase difference is less than 3° at the 900-MHz band. For the 1800-MHz band, a 0.3-dB amplitude unbalance and a 2° phase difference are observed.

IV. Conclusion

A new dual-band resonator configuration, called partially coupled stepped-impedance coupled-line resonators, has been proposed and mathematically investigated for dual-band applications. In addition, a novel dual-band balun using such a resonator configuration has been proposed. Based on an even- and odd-mode analysis technique, a design procedure and formula for the proposed balun have been developed. A prototype dual-band balun operating at 900 and 1800 MHz has been fabricated and measured to validate the theory. Measured results show that the proposed dual-band balun exhibits a good amplitude balance, as well as phase difference requirement within the two designed operating frequency bands. The proposed new resonator configuration can be found useful in many other dual-band applications where coupled-line resonators are traditionally used.

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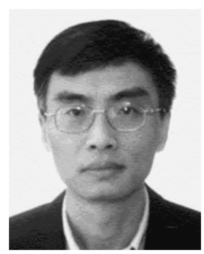

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