Multisection Impedance-Transforming Coupled-Line Baluns

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***Abstract*—A new class of multisection impedance-transforming coupled-line baluns is presented in this paper. It is based on the quarter-wavelength coupled-line balun. By cascading several coupled and uncoupled-line sections, broad-band baluns with good amplitude and phase balance can be realized using simple microstrip coupled lines. The resulting circuit has a simple structure with minimal discontinuities that is highly suited for very high-frequency applications. Simple design equations and experimental verifications will be presented. Using micostrip coupled sections with even-mode impedance of 159 Ω, the fabricated balun achieved 0.5-dB amplitude balance over 30% bandwidth. With higher even-mode impedance, almost perfect amplitude balance was achieved over 100% bandwidth.**

***Index Terms*—Baluns, coupled lines, impedance transformation, multisections.**

I. Introduction

BALUNS ARE key components in balanced circuit topologies such as balanced mixers, frequency multipliers, push–pull amplifiers, and antenna feed networks. Recently, it has also been shown that baluns can be used to form 180° hybrids [1], which further widens their applications. Various balun configurations have been reported for applications in microwave integrated circuits (MICs) and monolithic microwave integrated circuits (MMICs) [2]–[8]. Many of these structures, however, are not easily realized with commonly used microstrip structures or well suited for very high-frequency applications.

Most balun configurations consist of sections of transmission lines or coupled lines. The simplest transmission-line balun is probably a half-wavelength transmission line, but it is inherently narrow-band. Multiple sections of half-wavelength lines can be interconnected by quarter-wavelength lines for improved bandwidths [2], [3]. However, these introduce numerous T-junction discontinuities. At very high frequencies where the junction widths become comparable to quarter-wave lengths, these discontinuities may cause significant undesirable parasitics.

Coupled-line baluns can be broadly grouped under quarter-wave coupled-line baluns [4], [5], and Marchand coupled-line baluns [6]–[8]. Quarter-wave coupled baluns have a severe requirement for very high even-mode impedances to reject even-mode excitations [4]. High even-mode impedances are also required in Marchand baluns for broad-band performance. Consequently, these baluns have to be implemented using tightly coupled structures, which require metallization on both sides of the substrate or some nonplanar structure. These include broadside-coupled lines on suspended substrates [5] or multilayer structures [6], [7]. Even when edge-coupled microstrips are used, they have to be multiline couplers requiring several crossovers, like the Lange coupler [8]. Therefore, it will be very beneficial if baluns can be implemented using simple microstrip coupled lines.

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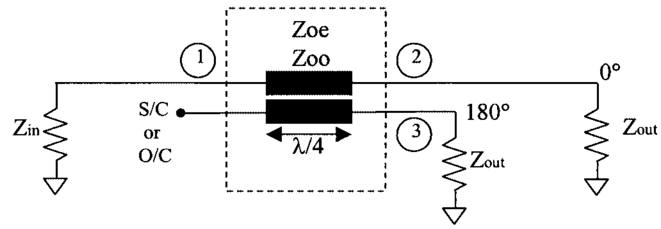

Fig. 1. Schematic diagram of a quarter-wave coupled-line balun.

In this paper, coupled-line baluns are realized by using only two-line edge-coupled microstrips. By cascading several of these coupled-line sections, very high even-mode impedances can be obtained, yielding good balun amplitude and phase balance. Simple design equations, taking into account the requirement for impedance transformation between the unbalanced and balanced ports, will be presented. In addition, it will also be shown that, in the multisection balun, the conventional coupled-line balun with a short-circuited terminal can be replaced by its dual circuit, which has an open-circuited terminal. This will further simplify the balun structure by eliminating the need for via-holes. Therefore, the proposed balun structure can be easily realized without significant discontinuities, making it well suited for planar circuits and very high-frequency applications. The design and performance of these multisection coupled-line baluns will be presented in this paper.

II. Theory

Fig. 1 shows the schematic diagram of a quarter-wave coupled-line balun. It provides balanced outputs to load terminations Z_{out} from an unbalanced input with source impedance Z_{in}. In general, the impedances Z_{in} and Z_{out} are different. For example, in a balanced diode mixer, balanced signals need to be fed to a pair of diodes, whose impedance may differ from the 50-Ω source impedance. Thus, in addition to providing balanced outputs, the balun also needs to perform impedance transformation between the source and load impedances.

As shown in Fig. 1, the balun consists of a pair of coupled lines, which are $\lambda/4$ at the center frequency of operation. One of the coupled-line terminals is terminated with full reflection, most commonly in a short circuit [4], [5]. However, it will be shown that an open circuit can be used in some cases.

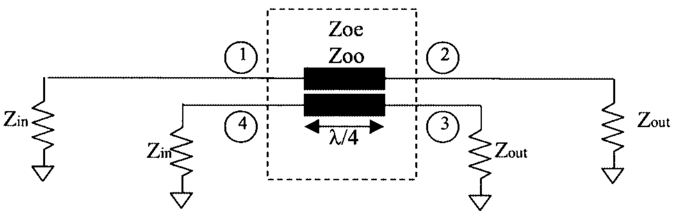

Fig. 2. Corresponding symmetrical four-port network for even- and odd- mode analysis.

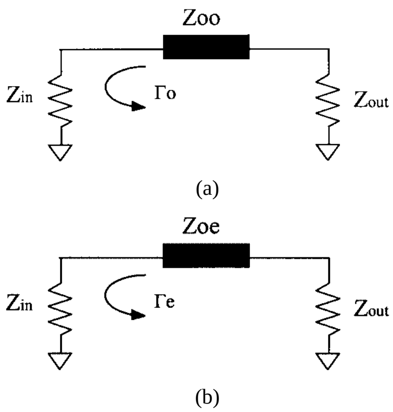

Fig. 3. (a) Odd-mode circuit. (b) Even-mode circuit of the corresponding symmetrical four-port network in Fig. 2.

With the port assignments given in Fig. 1, the S-parameters characterizing the balun operation are given by

$$S_{11} = 0 \tag{1a}$$
$$S_{21} = -S_{31}. \tag{1b}$$

The coupled-line odd- and even-mode impedances required for this balun operation can be derived from the corresponding four-port network shown in Fig. 2. In Fig. 2, the short- or open-circuited terminal is replaced by a load $Z_{\rm in}$ to form a symmetrical network. This facilitates the decomposition of the network into odd- and even- mode circuits shown in Fig. 3(a) and (b), respectively. It can be shown [9] that (1) will be satisfied when the reflection coefficients in the odd- and even-mode circuits of Fig. 3 are given by the following:

$$\text{for short-circuited case: } \Gamma_o = -\frac{1}{3} \quad \Gamma_e = 1 \tag{2a}$$
$$\text{for open-circuited case: } \Gamma_o = \frac{1}{3} \quad \Gamma_e = -1. \tag{2b}$$

Therefore, the required odd- and even-mode impedances can be derived as follows:

$$\text{for short-circuited case: } Z_{\rm oo} = \sqrt{\frac{Z_{\rm in}Z_{\rm out}}{2}}$$
$$Z_{\rm oe} = \infty \text{ (open circuit)} \tag{3a}$$
$$\text{for open-circuited case: } Z_{\rm oo} = \sqrt{2Z_{\rm in}Z_{\rm out}}$$
$$Z_{\rm oe} = 0 \text{ (short circuit)}. \tag{3b}$$

The above equations illustrate the difficulties in implementing the coupled-line balun. To approximate the required open or short circuits in the even mode, very high or very low even-mode impedances is required. The use of insufficiently high or low even-mode impedances will result in degradation of the balun balance. This imbalance can be quantify by the ratio of S_{21}/S_{31} [4] as follows:

$$\text{for short-circuited case: } \frac{S_{31}}{S_{21}} = -\frac{Z_{\rm oe} - Z_{\rm oo}}{Z_{\rm oe} + Z_{\rm oo}} \tag{4a}$$
$$\text{for open-circuited case: } \frac{S_{31}}{S_{21}} = \frac{Z_{\rm oe} - Z_{\rm oo}}{Z_{\rm oe} + Z_{\rm oo}}. \tag{4b}$$

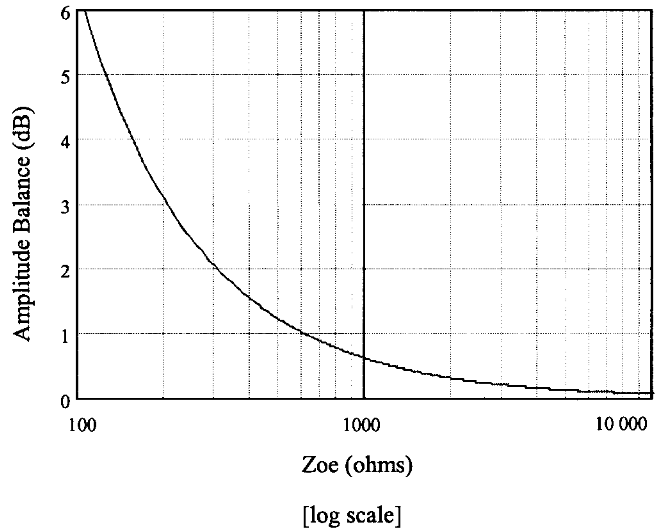

Fig. 4. Amplitude balance variation with $Z_{\rm oe}$ for the short-circuited coupled-line balun ($Z_{\rm in} = Z_{\rm out} = 50\ \Omega$ and $Z_{\rm oo} = 35\ \Omega$).

Equation (4) shows that phase balance is ensured at the center frequency when $Z_{\rm oe} > Z_{\rm oo}$ for the short-circuited case, and when $Z_{\rm oe} < Z_{\rm oo}$ for the open-circuited case. For most coupled-line structures, $Z_{\rm oe}$ is greater then $Z_{\rm oo}$. Therefore, the short-circuit case is the most common, where broadside-coupled-line suspended striplines [5] or tightly coupled microstrip lines [2] are employed to achieve the required high $Z_{\rm oe}$ and specific $Z_{\rm oo}$. However, by using coupled slot lines [10], where $Z_{\rm oe} < Z_{\rm oo}$, the open circuit case can also be feasible.

The balun amplitude balance, however, degrades rapidly with nonideal open or short circuits. This is illustrated in Figs. 4 and 5, which plot the amplitude balance variation with $Z_{\rm oe}$ for the short- and open-circuit cases, respectively. Both plots are for $Z_{\rm in} = Z_{\rm out} = 50\ \Omega$, which gives $Z_{\rm oo} = 35\ \Omega$ for the short-circuit case and $Z_{\rm oo} = 71\ \Omega$ for the open-circuit case.

For the short-circuit case in Fig. 4, $Z_{\rm oe}$ needs to be over 1000 Ω to achieve amplitude balance of less than 0.5 dB. This is clearly not realizable in most coupled-line structures. For example, in commonly used microstrip or stripline coupled lines, $Z_{\rm oe}$ is typically less than 200 Ω, which will result in amplitude balance of over 3 dB. Conversely for the open-circuit case in Fig. 5, 0.5-dB amplitude balance requires $Z_{\rm oe}$ to be below 2 Ω, while $Z_{\rm oe}$ of coupled slot lines is typically a few tens of ohms.

In this paper, the multisection coupled-line balun is proposed to effectively increase or decrease $Z_{\rm oe}$ of coupled lines to the high or low values required by the coupled-line balun. As shown in Fig. 6, it consists of a cascade of n coupled-line sections, with the i section having even- and odd-mode impedances $Z_{\rm oei}$ and $Z_{\rm ooi}$.

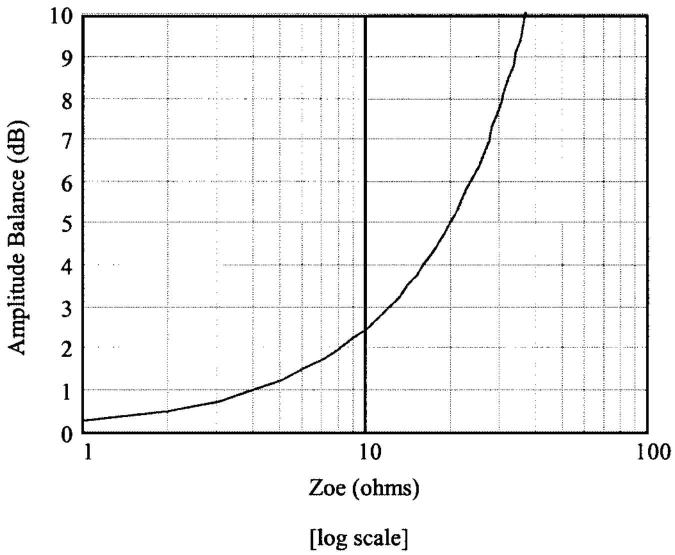

Fig. 5. Amplitude balance variation with $Z_{\rm oe}$ for the open-circuited coupled-line balun ($Z_{\rm in} = Z_{\rm out} = 50\ \Omega$ and $Z_{\rm oo} = 71\ \Omega$).

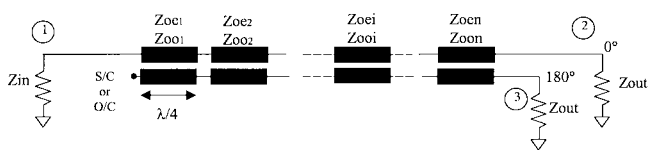

Fig. 6. Schematic diagram of the multisection coupled-line balun.

By decomposing the multisection coupled-line balun into the corresponding odd- and even-mode circuits, like the single-section balun in Fig. 3, equivalence between the two baluns can be found. Specifically, at the center frequency, where each coupled section is $\lambda/4$ long, the multisection balun is equivalent to a single-section coupled-line balun with odd- and even-mode impedances given by the following:

$$\text{when } n = \text{odd:}\quad Z_{\rm oo} = \frac{Z_{\rm oo1} Z_{\rm oo3}, \ldots, Z_{\rm oon}}{Z_{\rm oo2} Z_{\rm oo4}, \ldots, Z_{{\rm oo}(n-1)}}, \qquad Z_{\rm oe} = \frac{Z_{\rm oe1} Z_{\rm oe3}, \ldots, Z_{\rm oen}}{Z_{\rm oe2} Z_{\rm oe4}, \ldots, Z_{{\rm oe}(n-1)}} \tag{5a}$$

$$\text{when } n = \text{even:}\quad Z_{\rm oo} = \frac{Z_{\rm oo1} Z_{\rm oo3}, \ldots, Z_{{\rm oo}(n-1)} Z_{\rm out}}{Z_{\rm oo2} Z_{\rm oo4}, \ldots, Z_{\rm oon}}, \qquad Z_{\rm oe} = \frac{Z_{\rm oe1} Z_{\rm oe3}, \ldots, Z_{{\rm oe}(n-1)} Z_{\rm out}}{Z_{\rm oe2} Z_{\rm oe4}, \ldots, Z_{\rm oen}}. \tag{5b}$$

Therefore, the effective $Z_{\rm oe}$ can be increased or decreased by cascading coupled-line sections with $Z_{\rm oei}$ alternating between high and low values. This is equivalent to the design of a low-pass filter to present an open or short circuit in the stopband. Specifically, $Z_{\rm oe1}, Z_{\rm oe3}, \ldots,$ etc. are set high, while $Z_{\rm oe2}, Z_{\rm oe4}, \ldots,$ etc. are set low to achieve high effective $Z_{\rm oe}$. Conversely, $Z_{\rm oe1}, Z_{\rm oe3}, \ldots,$ etc. are set low, while $Z_{\rm oe2}, Z_{\rm oe4}, \ldots,$ etc. are set high to achieve low effective $Z_{\rm oe}$. Therefore, one can effectively set $Z_{\rm oe} \gg Z_{\rm oo}$ or $Z_{\rm oe} \ll Z_{\rm oo}$ to implement the short- or open-circuit case.

The odd-mode impedances $Z_{\rm oo1}, Z_{\rm oo2}, \ldots, Z_{\rm oon}$ are set such that the matching condition in (3) is satisfied. This is equivalent to the design of a multisection $\lambda/4$ impedance transformer.

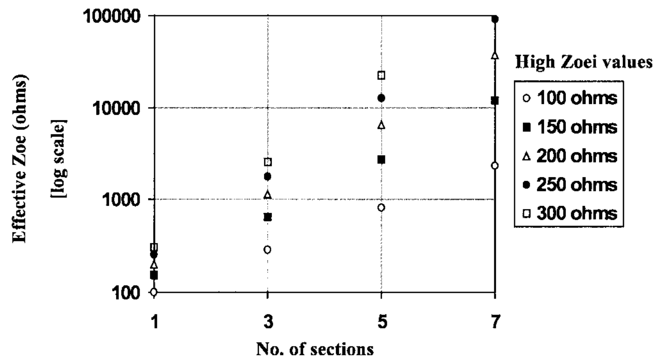

Fig. 7. Effective $Z_{\rm oe}$ with an increasing number of sections for the short-circuited coupled-line balun ($Z_{eo2} = Z_{\rm oe4}, \ldots, = Z_{{\rm oe}(n-1)} = 35\ \Omega$).

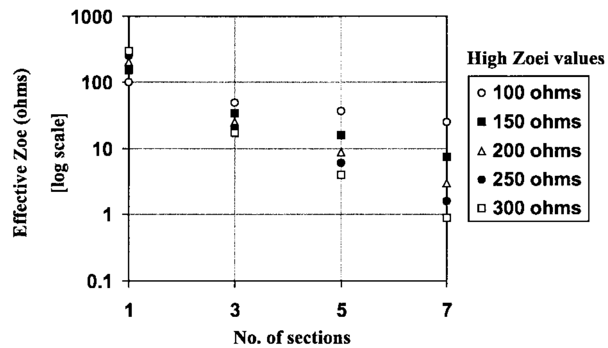

Fig. 8. Effective $Z_{\rm oe}$ with an increasing number of sections for the open-circuited coupled-line balun ($Z_{\rm oe1} = Z_{\rm oe3}, \ldots, = Z_{\rm oen} = 71\ \Omega$).

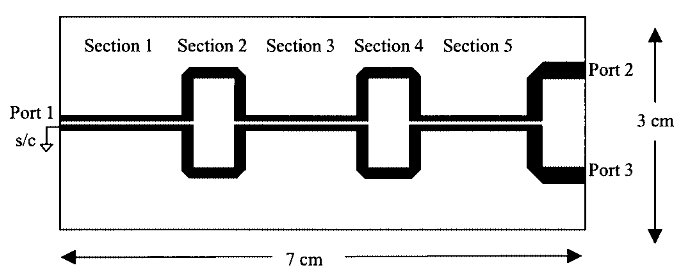

Fig. 9. Layout of the fabricated five-section microstrip coupled-line balun.

Therefore, these impedances may be set to yield a specific passband performances. For example, when $Z_{\rm in} = Z_{\rm out} = 50\,\Omega$ and n = odd, one can set $Z_{\rm oo1} = Z_{\rm oo2}, \ldots, = Z_{\rm oon} = 35\ \Omega$ for the short-circuit case and $Z_{\rm oo1} = Z_{\rm oo2}, \ldots, = Z_{\rm oon} = 71\,\Omega$ for the open-circuit case to achieve a Chebyshev passband response with a fractional bandwidth of 2 [11].

Practically, there is an additional constrain that $Z_{\rm oe1} > Z_{\rm oo1}, Z_{\rm oe2} > Z_{\rm oo2}, \ldots, Z_{\rm oei} > Z_{\rm ooi} \ldots, Z_{\rm oen} > Z_{\rm oon}$ for most coupled structures. This limits the low $Z_{\rm oei}$ that can be used when cascading coupled-lines sections with alternating high and low $Z_{\rm oei}$ values. The lowest achievable $Z_{\rm oei}$ is when $Z_{\rm oei} = Z_{\rm ooi}$, i.e., is the use of uncoupled transmission lines. The highest realizable $Z_{\rm oei}$, on the other hand, depends on the transmission-line medium used and is limited by the fabrication tolerances.

Based on the above example, Figs. 7 and 8 plot the effective $Z_{\rm oe}$ achievable with an increasing (odd) number of sections for realizable high $Z_{\rm oei}$ values of 100, 150, 200, 250, and 300 Ω. For the short-circuit case in Fig. 7, all the low $Z_{\rm oei}$ impedances are

TABLE I
IMPEDANCE VALUES AND DIMENSIONS FOR THE COUPLED-LINE BALUN IN FIG. 9

	Section 1	Section 2	Section 3	Section 4	Section 5
Zoei (ohm)	159	59	159	59	159
Zooi (ohm)	50	59	50	59	50
Trace width (mm)	0.5	2.1	0.5	2.1	0.5
Coupling gap (mm)	0.15	_	0.15	_	0.15

set equal to the required odd-mode impedances. That is, $Z_{\rm oe2} = Z_{\rm oe4} =, \ldots, = Z_{\rm oe}(n-1) = 35\ \Omega$. Similarly, for the open-circuit case in Fig. 8, $Z_{\rm oe1} = Z_{\rm oe3}, \ldots, = Z_{\rm oen} = 71\ \Omega$.

As shown in Fig. 7, the effective $Z_{\rm oe}$ increases rapidly with an increasing number of sections when the realizable $Z_{\rm oei}$ is high. For example, to achieve an effective $Z_{\rm oe}$ above 1000 Ω with a realizable $Z_{\rm oei}$ of 100 Ω, seven sections are required. For realizable $Z_{\rm oei}$ values of 150 and 300 Ω, the number of sections required reduces to five and three, respectively. Similarly, for the open-circuit case in Fig. 8, a higher realizable $Z_{\rm oei}$ reduces the number of sections required to achieve a specific low effective $Z_{\rm oe}$.

Based on the impedance requirements given in Figs. 4 and 5, one can estimate the number of sections required for a specific amplitude balance using Figs. 7 and 8. Using these figures, it is apparent that, for the same high $Z_{\rm oei}$ value, the short-circuit case gives a better amplitude balance than the open-circuit case. This is because, for the above example, the ratio of high-to-low $Z_{\rm oei}$ values is larger in the short-circuit case than in the open-circuit case. Practically, the larger ratio of high-to-low $Z_{\rm oei}$ will also result in an even-mode low-pass filter with wider stopband. Consequently, the balun bandwidth will also be increased.

III. EXPERIMENTAL RESULTS

To demonstrate the proposed technique and validate the analytical results, two mutisection coupled-line baluns were designed for the short-circuited case. These baluns were fabricated on low-cost FR-4 boards with a dielectric constant of 4.5 and a thickness of 1.5 mm. The microstrip traces are defined by a T-tech printed circuit board (PCB) router.

Fig. 9 shows the layout of the first coupled-line balun. It employs simple microstrip coupled lines. To achieve the highest $Z_{\rm oei}$ within fabrication tolerances, the coupled-line widths and gaps are fixed at 0.5 and 0.15 mm, respectively. This gives a $Z_{\rm oei}$ of 159 Ω. Using Figs. 4 and 7 as guides, at least five sections are needed to achieve an effective $Z_{\rm oe}$ of approximately 1000 Ω for an amplitude balance of 0.5 dB. Table I shows the dimensions and impedances for the five sections. Sections 1, 3, and 5 are identical coupled sections for high $Z_{\rm oei}$, while sections 2 and 4 are identical uncoupled sections for low $Z_{\rm oei}$. The odd-mode impedances are designed to transform the 50-Ω load impedance to the required 25 Ω at the source termination. Sections of 50-Ω microstrip lines were used to extend ports 2 and 3 for measurement. The short circuit was obtained by soldering a strip of copper around the edge of the substrate.

Fig. 10 shows the measured amplitude response of the five-section coupled-line balun. Also shown are the simulation results

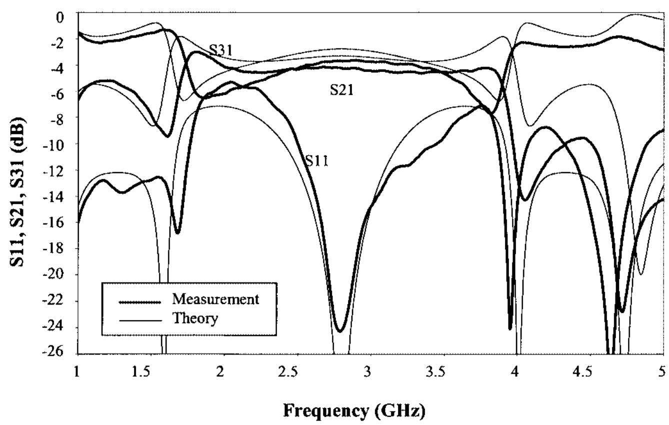

Fig. 10. Measured and theoretical amplitude response of the five-section coupled-line balun.

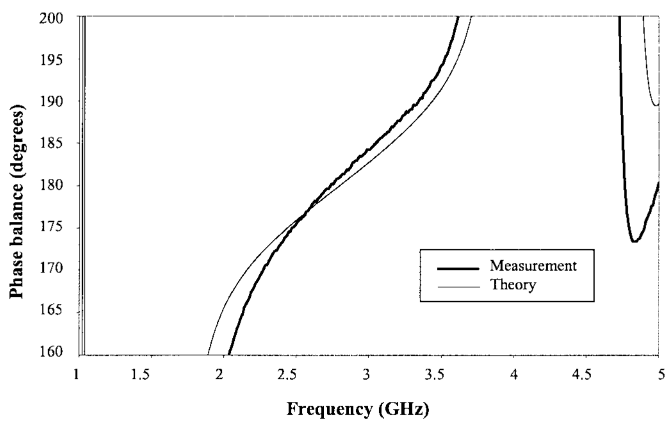

Fig. 11. Measured and theoretical phase balance of the five-section coupled-line balun.

using Agilent's ADS software,[1] based on ideal transmission lines with the impedances given in Table I. The input is well matched at the center frequency of 2.8 GHz. Based on an input return loss of 10 dB, the operational bandwidth is approximately 30%. The amplitude balance at mid-band is approximately 0.5 dB, which is in agreement with the theoretical result for the designed effective $Z_{\rm oe}$ of 1155 Ω. The phase balance is $\pm 8^{\circ}$ within the passband, as shown in Fig. 11.

The above balun example shows that coupled-line baluns can be implemented using simple microstrip line couplers. The multisection structure allows good amplitude balance to be achieved even with relatively low $Z_{\rm oei}$. With higher $Z_{\rm oei}$,

[1]*Agilent Advanced Design System (ADS)*, ver. 1.3, Agilent Technol. Inc., Palo Alto, CA.

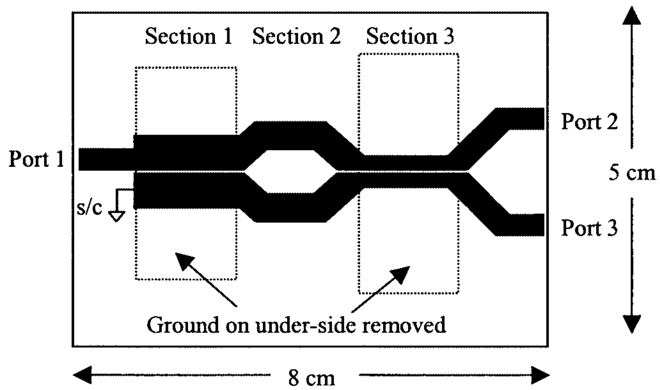

Fig. 12. Layout of fabricated three-section microstrip coupled-line balun with tuning septums.

TABLE II
IMPEDANCE VALUES AND DIMENSIONS FOR THE COUPLED-LINE BALUN IN FIG. 12

	Section 1	Section 2	Section 3
Zoei (ohm)	192	35	301
Zooi (ohm)	33	35	38
Trace width (mm)	7	5	2.5
Coupling gap (mm)	0.15	_	0.15
Septum width (mm)	44.15		45.15

better balun balance with increased bandwidth can be achieved using a smaller number of sections. To achieve these advantages, a multisection balun employing coupled sections with higher $Z_{\rm oei}$ was also implemented. To maintain a simple coupling structure without resorting to multiple layers and crossovers, microstrip coupled-lines with tuning septums [12] were employed. The circuit layout is shown in Fig. 12.

The microstrip coupled-line sections have a tuning septum whereby a slot is cut in the ground plane beneath the coupled lines. The slot length is equal to the coupled-line length and the slot widths can be tuned to achieve high $Z_{\rm oei}$ without significant effect on $Z_{\rm ooi}$. Using this technique, $Z_{\rm oei}$ values of 300 Ω can be realized, and a three-section balun is sufficient to achieve good amplitude balance. The $Z_{\rm ooi}$ impedance is mainly determined by the coupled-line width and gap. As in the previous balun, the coupling gap is fixed at 0.15 mm. Table II shows the dimensions and impedances of the line sections. The $Z_{\rm ooi}$ and $Z_{\rm oei}$ for the coupled-line sections are calculated using the commercially available electromagnetic (EM) software HFSS.[2] The odd-mode impedances in this balun are designed to achieve a three-section Chebyshev transformer response. The short circuit was implemented by soldering a copper strip through a via.

Fig. 13 shows the measured response together with the theoretical results. Due to the higher $Z_{\rm oei}$ in the coupled sections, almost perfect amplitude balance is now achieved throughout the balun passband. The operational bandwidth is also increased to approximately 100%, from 1 to 3 GHz. The phase balance has also improved to $\pm 5^\circ$ within the passband, as shown in Fig. 14.

[2]*Agilent High Frequency Structures Simulator (HFSS),* ver. 5.4, Agilent Technol. Inc., Palo Alto, CA.

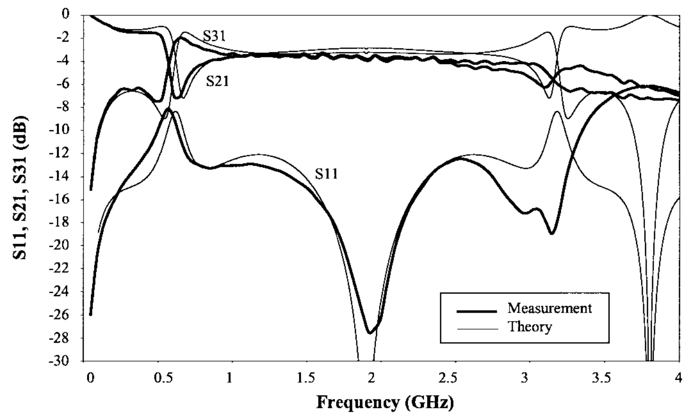

Fig. 13. Measured and theoretical amplitude response of the three-section coupled-line balun.

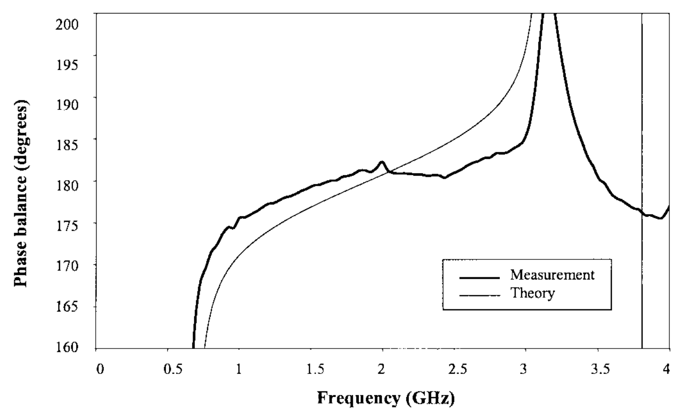

Fig. 14. Measured and theoretical phase balance of the three-section coupled-line balun.

The measured results for the two fabricated baluns are generally in good agreement with the theoretical responses. Discrepancies between the two results can be attributed to the unaccounted microstrip losses, discontinuity parasitics, and the unequal odd- and even-mode phase velocities in the practical circuits.

IV. CONCLUSION

This paper has demonstrated that quarter-wave coupled-line baluns can be realized using simple microstrip coupled-line sections. By cascading several of these coupled sections together, the relative low even-mode impedances can be effectively increased to yield good balun amplitude and phase balance over a broad bandwidth. A five-section microstrip balun with coupled sections of 159-Ω even-mode impedance achieved 0.5-dB amplitude balance over a 30% bandwidth. With a higher even-mode impedance of 300 Ω, almost perfect amplitude balance was obtained over a 100% bandwidth using three sections. The direct cascading of microstrip coupled- and uncoupled-line sections also results in a simple circuit structure with minimal discontinuities. In addition, the multisection structure also allows realization of the open-circuited coupled-line balun, which is the dual circuit of the conventional short-circuit coupled-line balun. Therefore, the proposed multisection impedance-transforming baluns are highly useful in the design of planar balanced circuits, especially for very high-frequency applications.

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