A Derivation of a Class of 3-port Baluns from Symmetrical 4-port Networks

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***Abstract* — This paper describes an approach in deriving the general conditions that need to be satisfied for a class of 3-port baluns. This is done by analyzing the behavior of a general symmetrical 4-port network when one of the ports is terminated with an arbitrary impedance. These conditions will be useful in devising new balun structures and in deriving exact design equations for such baluns. Examples will be presented for some known and new baluns in this class. These insights have also made the cascading of multi-section baluns possible by specifying the overall requirements for the cascaded structures. Based on these results, a 3-section, Marchand-type, coupled-line balun has been designed and fabricated. Good agreements between simulation and measured results have been obtained, thereby verifying the validity of the design equations.**

I. Introduction

Three-port baluns are important circuit components to realize critical circuit functions such as double-balanced mixers, frequency multipliers, push-pull amplifiers, 180^0 hybrid [1], etc. Many of these 3-port baluns belong to the same class, where they are composed of symmetrical 4-port networks with one of the ports terminated with an arbitrary impedance. Some examples include the coupled-line Marchand balun [2] and the N-section halfwave balun [3]. Although there are previous works [4]-[5] analyzing specific configurations of this class of baluns, a generalized analysis is not available. A technique for analyzing 3-port baluns as generalized symmetrical 4-ports is presented in this paper. This technique gives valuable insight to the synthesis of the baluns by specifying the requirements of the odd and even mode parameters of the 4-port symmetrical networks. This results in the development of new balun structures and exact, closed-form design equations at the center frequency of operation for known baluns in this class. Some examples of these baluns will be illustrated.

II. Theory

For the class of baluns that we are interested in, the 3-port baluns are formed by terminating one of the ports of symmetrical 4-port networks with an arbitrary impedance, Γ, as shown in Figure 1.

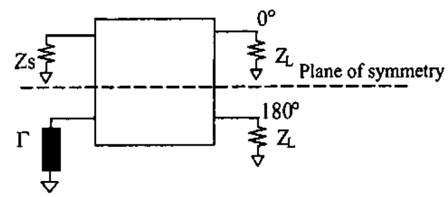

Fig. 1. Configuration of the 3-port balun that is analyzed in this work. It is constructed from a 4-port network that is symmetrical about the dashed line.

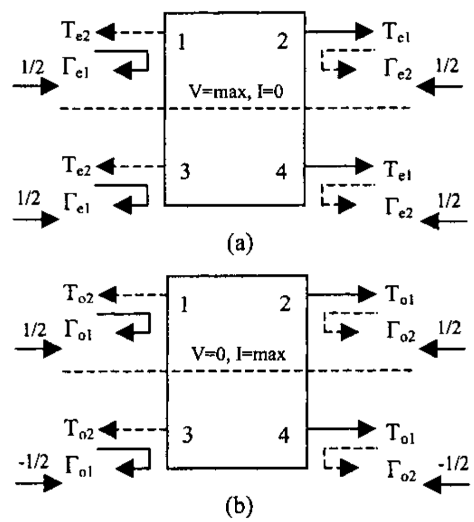

Fig. 2. Decomposition of the symmetrical 4-port network into even- and odd-mode excitations. (a) Even mode; (b) Odd mode.

The 4-port symmetrical network is first analyzed by using even- and odd-mode excitations, as shown in Figure 2, to derive its S-matrix in terms of the even/odd-mode reflection and transmission coefficients. The 4-port S-matrix is reduced to a 3-port S-matrix, by imposing the boundary condition at the reflection port of the 4-port network as shown in Figure 1. The following conditions need to be satisfied in order for the final 3-port network to behave as a balun:

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

and

$$S_{11} = 0 \tag{2}$$

where port 1 is the input port and port 2, 3 are the output ports of the final 3-port.

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In addition, if $|\Gamma|=1$, and if the 4-port network is lossless, the power at each output port will be –3 dB with respect to the input power. By substituting the derived 3-port S-Matrix elements into (1) and (2), requirements for the final 3-port network to behave as a balun can be specified in terms of the even- and odd-mode parameters of the symmetrical 4-port network.

III. CONDITIONS FOR SYNTHESIZING 3-PORT BALUNS

The above approach has been used to derive the conditions for synthesizing 3-port baluns as illustrated in Figure 1 and the conditions are listed as follows:

$$\frac{T_{el}\cdot(1-\Gamma_{ol}\cdot\Gamma)}{2-\Gamma\cdot(\Gamma_{el}+\Gamma_{ol})}=0 \quad (3)$$

and

$$\frac{\Gamma_{el}+\Gamma_{ol}-2\cdot\Gamma_{el}\cdot\Gamma_{ol}\cdot\Gamma}{2-\Gamma\cdot(\Gamma_{el}+\Gamma_{ol})}=0 \quad (4)$$

IV. APPLICATIONS

Different values of Γ have been evaluated with the above conditions. The following 2 sets of conditions have been found to be most practical and useful:

$\Gamma=+1$: $\Gamma_{el}=-1$, and $\Gamma_{ol}=+1/3$ (5)

$\Gamma=-1$: $\Gamma_{el}=+1$, and $\Gamma_{ol}=-1/3$ (6)

This implies that a balun can be formed if the 4-port symmetrical network behaves as transmission-stop network in the even-mode excitation and as an impedance transformer in the odd-mode excitation. Based on these conditions, 6 baluns have been synthesized and tabulated in Figure 3.

The topology of the balun listed in Figure 3f is new and the exact design equations and design curves for most of the baluns listed have not been published previously. The baluns listed in Figure 3a and 3b are easy to implement in planar form but they are limited in bandwidth as compared to the coupled-line baluns. The balun described in Figure 3b can be viewed as a dual of the balun in Figure 3a. It provides a convenient point at the RF-short-circuit terminal to introduce DC biasing circuitry. The balun in Figure 3e has the characteristic of having lower coupling requirement on the coupled-lines as the load resistance decreases. This is useful when the balun is used to construct push-pull amplifiers, as the devices' impedances are usually low.

All the baluns listed in Figure 3 have band-pass type of response, as the odd-mode topologies of their symmetrical 4-port networks are band-pass in nature. The bandwidth of the baluns will be limited by the choice of topology of the balun. All the baluns listed in Figure 3 can be cascaded with more sections of the same kind provided that the overall structure obeys condition (3) and (4). This will enhance the rejection of the balun at out-of-band frequencies. As it will be shown below, the multi-section balun integrates the functions of a balun and a filter into a single circuit.

V. EXPERIMENTAL VERIFICATION

A 3-section Marchand-type, coupled-line microstrip balun operating from 2.3 GHz to 2.5 GHz, has been designed and fabricated with a substrate of Er=2.2 and 31 mil in height. Each section of the balun has the same topology as listed in Figure 3c and the even- and odd-mode characteristic impedances of each section are listed in Table 1. Section 1 denotes the section that is closer to the input of the balun.

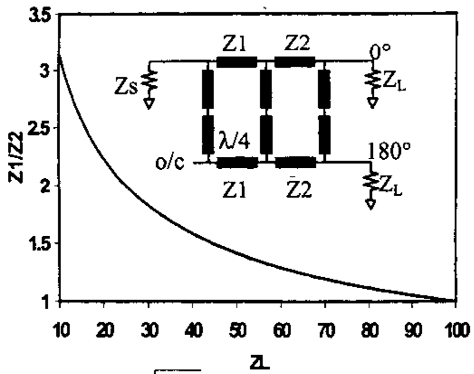
TABLE 1
EVEN- AND ODD-MODE CHARACTERISTIC IMPEDANCES OF THE 3-SECTION BALUN

	Section1	Section2	Section3
Z_{oe}	135	94	95
Z_{oo}	61	66	43

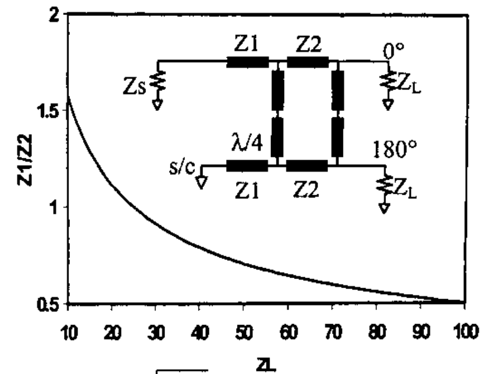
In the odd-mode configuration, the 3-section coupled-line pairs transform the output 50-Ohm load towards a 100-Ohm input resistance across the frequencies of operation. In the even-mode configuration, a short-circuit termination is presented at the input of the balun. Simulation was done in ADS™ by using microstrip coupled-line model, taking into account of the fabrication errors. Care has to be taken in cascading to prevent forward-wave coupling from propagating in-band in the even-mode configuration, which is caused by the different odd- and even-mode phase velocities. Figure 4 shows the photograph and schematic of the balun and Figure 5(a) shows the measured and simulated transmission and reflection response of the balun. Figure 5(b) illustrates the measured and simulated phase balance of the balun. Close agreements have been achieved between the simulated and the measured response.

VI. CONCLUSION

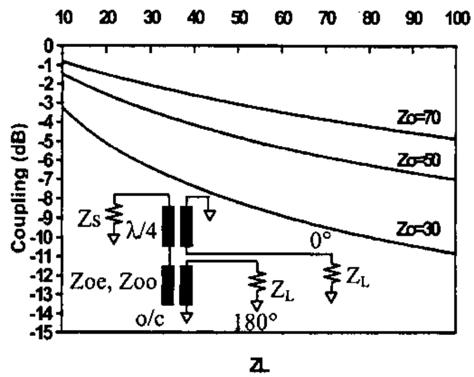
This paper describes an approach to derive the conditions for synthesizing a class of 3-port baluns from symmetrical 4-port networks. These conditions will result in devising new balun structures and in deriving the exact design equations for these baluns in the center frequency of operation. Useful design equations and design curves for some known and new baluns have been derived by using this approach, and the results are presented in the



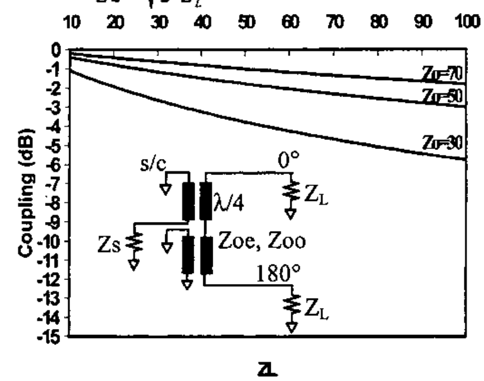
(a) $\frac{Z1}{Z2}=\sqrt{\frac{2\cdot Zs}{Z_L}}$



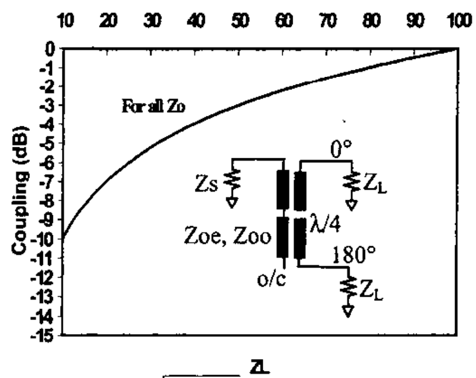
(b) $\frac{Z1}{Z2}=\sqrt{\frac{Zs}{2\cdot Z_L}}$



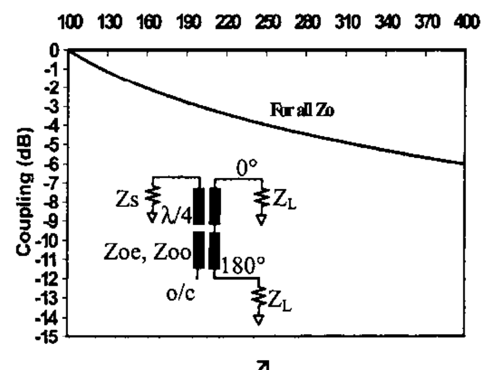
(c) $Zoo=\frac{-Zo^2+Zo\cdot\sqrt{Zo^2+2\cdot Zs\cdot Z_L}}{\sqrt{2\cdot Zs\cdot Z_L}}$ $\quad Zoe=\frac{Zo^2}{Zoo}$



(d) $Zoo=\frac{-\sqrt{2}\cdot Zo^2+Zo\cdot\sqrt{2\cdot Zo^2+Zs\cdot Z_L}}{\sqrt{Zs\cdot Z_L}}$ $\quad Zoe=\frac{Zo^2}{Zoo}$



(e) $Zoo=Zo\cdot\sqrt{\frac{\sqrt{\frac{2\cdot Zs}{Z_L}}-1}{\sqrt{\frac{2\cdot Zs}{Z_L}}+1}}$ $\quad Z_L<2\cdot Zs \quad Zoe=\frac{Zo^2}{Zoo}$



(f) $Zoo=Zo\cdot\sqrt{\frac{\sqrt{\frac{Z_L}{2\cdot Zs}}-1}{\sqrt{\frac{Z_L}{2\cdot Zs}}+1}}$ $\quad Z_L>2\cdot Zs \quad Zoe=\frac{Zo^2}{Zoo}$

Fig. 3. Topologies, design curves, and design equations for 6 balun synthesized from eqn (5) and (6). The design curves are for cases with Zs=50 Ohm and various Zo.

paper. A 3-section, Marchand-type, coupled-line balun, centered at 2.4 GHz have been designed and fabricated. Good agreements between simulation and measured results have been obtained, thereby verifying the validity of the design equations. The valuable insights given by this analysis approach will lead to the development of more novel balun structures and their design equations.

ACKNOWLEDGEMENT

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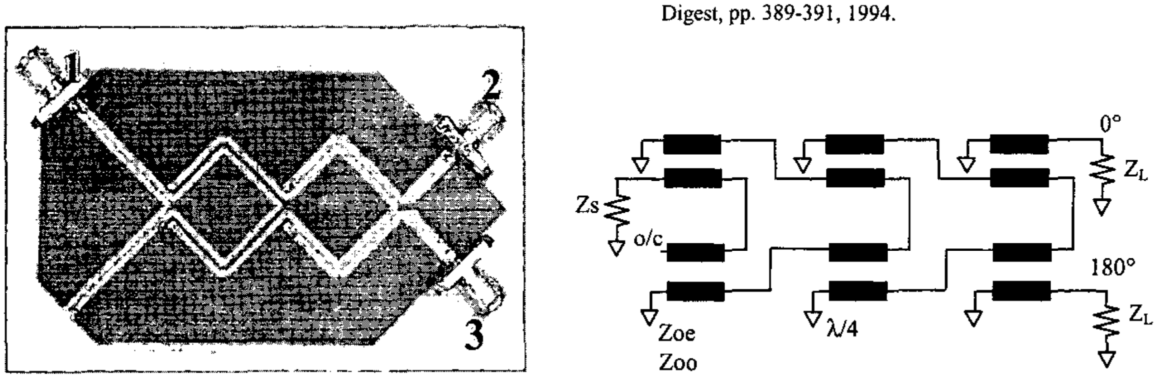
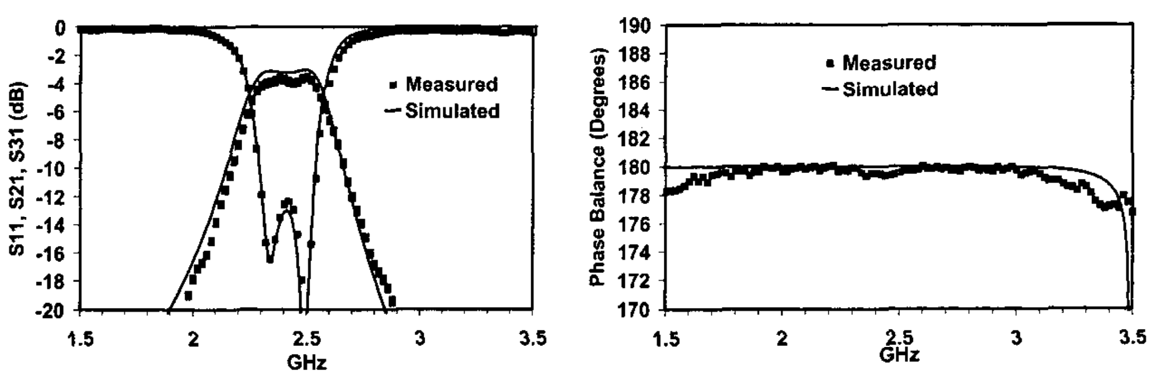


(a) (b)

Fig. 4. (a) Photograph of a 3-section Marchand balun centered at 2.4 GHz; (b) Schematic of the 3-section Marchand balun.



(a) (b)

Fig. 5. (a) S11, S21 and S31; (b) Phase balance of the 3-section Marchand balun. The response of S21 and S31 are overlapping on each other.