Broadband Balun Circuits Composed of Impedance Transforming Directional Couplers and LH Transmission-Line Sections

J. Sorocki, I. Piekarz, K. Staszek, P. Kaminski, K. Wincza, and S. Gruszczynski

***Abstract*—In this paper, a new approach to the design of a balun circuit is presented. The proposed balun is composed of an impedance-transforming directional coupler and an LH/RH transmission line differential phase shifter. The proposed solution features broadband amplitude and phase response, moreover, a flexibility of the impedance transformation from balanced to imbalanced port is obtained. The proposed concept has been verified by the design of a balun circuit featuring over-an-octave bandwidth and impedance transformation 70 $\Omega_{bal.}$ / 50 Ω_{imbal}.**

***Index Terms*—Microwave baluns, directional couplers, coupled-line couplers.**

I. Introduction

Baluns are well-known microwave circuits allowing for conversion of unbalanced mode propagating in asymmetric wave-guiding structures, e.g. microstrip lines, to a balanced one propagating in balanced lines. The design of such networks has been described in a number of papers [1]–[6]. Among typical solutions one can name tapered-line baluns [1], Marchand baluns [2]–[4] or baluns designed with the use of trans-directional couplers [5]. On the other hand a 0/180° coupled-line directional coupler can be utilized as a balun circuit. As a benefit, a wide operational bandwidth can be obtained, taking the advantage of the broadband properties of the utilized coupled-line sections. The exemplary design of such networks can be found in e.g. [6], [7], where 0/180° couplers have been designed as a connection of 3dB/90° directional couplers and 90° phase shifters. Moreover, in order to achieve wide operational bandwidth in terms of phase response, differential phase shifters utilizing left-handed (LH) and right-handed (RH) transmission-line sections have been applied. In such networks, however, the impedance terminating the balanced port needs to be equal twice the impedance terminating the imbalanced port i.e. $Z_{bal.} = 2Z_{imbal.}$ Therefore, the impedance transformation ratio defined as $R_b = Z_{bal.} / Z_{imbal}$ equals 2 and cannot be arbitrarily chosen.

In this paper, a novel concept of the balun circuit has been proposed, in which recently developed impedance-transforming directional couplers have been applied. In the proposed network, the impedance transformation is obtained by the properly designed coupled-line section as it was recently reported [8]. The required phase response of the network is obtained with the use of an additional differential phase shifter composed of LH and RH transmission-line sections, as it was presented in [6] and [7]. As a result, broadband amplitude and phase response of the balun circuit can be obtained. The proposed technique has been verified by the design of a balun circuit transforming the impedance terminating imbalanced port $Z_{imbal.}$ = 50 Ω to the impedance terminating balanced port $Z_{bal.}$ = 70 Ω (R_b = 1.4). The obtained measurement results are in a good agreement with the results of circuit and electromagnetic analyses.

Manuscript received December 9, 2014; revised January 20, 2016. This work was partially supported by the National Science Centre under contract no. DEC-2011/01/D/ST7/00789 and in part by the statutory activity of AGH Department of Electronics.

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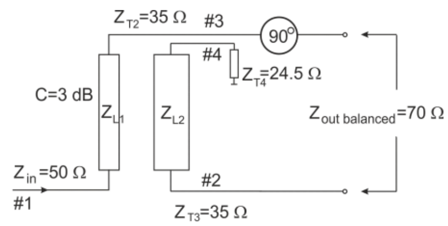
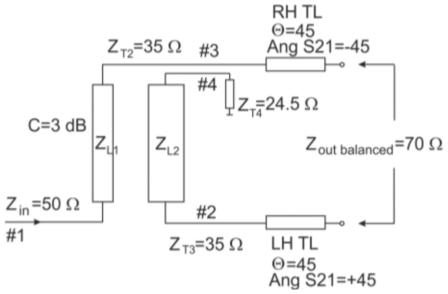
II. Analysis of the Proposed Balun Circuit

The concept of the proposed balun circuit is presented schematically in Fig. 1(a), where a circuit composed of a 90°-long coupled line section in conjunction with the ideal 90° phase shifter is presented.



(a)



(b)

Fig. 1. Schematic diagram of the proposed balanced circuit utilizing an impedance transforming directional coupler. Balun with an ideal 90° phase shifter (a) and with a differential phase shifter consisting of two 45°-long LH and RH transmission line sections (b).

If the coupled-line section is designed following the procedure shown in [8], the resulting coupled-line section transforms the impedance of the input port to the chosen impedance level at the coupled and transmission ports. As it was also shown in [8] the limiting value for the impedance transformation is related to the coupling factor k of the coupled-line section, and is expressed as follows:

$$R \leq \frac{1}{k^2} \quad (1)$$

Taking into account that in baluns equal power split needs to be ensured i.e. $k = 0.707$, the impedance transformation R cannot exceed 2. This condition, however, gives a flexibility for the realizable impedance transformation, which can be of any value from the range of 25 Ω < Z_{out} < 100 Ω (assuming Z_{in} = 50 Ω). The given range of output impedance of the coupled-line section Z_{out} results in a range of realizable balanced impedance 50 Ω < $Z_{bal.}$ <200 Ω, that can be achieved at the balanced output ports of the circuit.

To investigate the properties of the proposed circuit, a balun with impedance transformation $R_b = Z_{bal.} / Z_{imbal}$ = 70 Ω / 50 Ω has been designed, for which the coupling factor k = 0.8 has been selected, ensuring a wide operational bandwidth in terms of amplitude response. The required additional 90° differential phase shifter has been realized with the use of a technique reported in [6], [7], where a pair of LH and RH sections, both being 45°-long, have been applied (see Fig. 1(b). The resulting scattering parameters of the circuit are presented in Fig. 2.

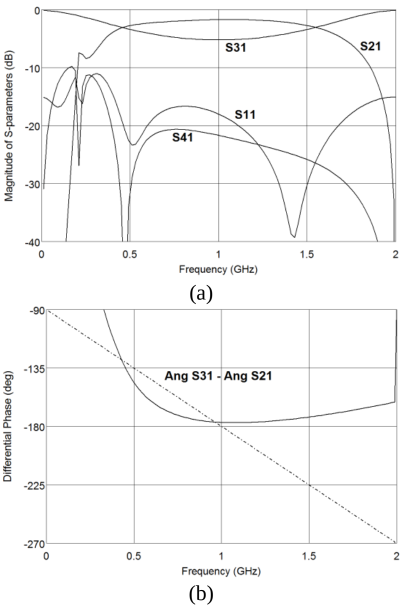
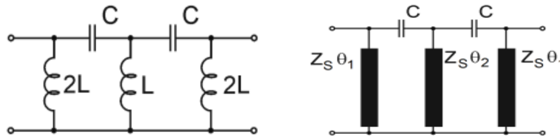


Fig. 2. Magnitude of S parameters of the designed broadband balun circuit (a), and its differential phase (solid line) (b) in comparison to the differential phase of a balun with 'RH-only' phase shifter (dashed line). Results of circuit analysis.

The proposed circuit features wide operational bandwidth in terms of both amplitude and phase response. Additionally in Fig. 2(b) a phase response of the balun circuit is shown, in which the required 90° phase shift is obtained using a 90°-long RH line at the transmission ports. From the comparison it is seen that the utilization of a metamaterial transmission line improves the phase imbalance in relatively wide frequency range. For the purpose of analysis the 45°-long LH transmission-line section has been approximated with the lumped element equivalent circuit presented in Fig. 3(a), for which the following values have been found C = 13 pF and L = 16 nH. Further, to allow for physical realization, a semi-distributed approximation has been employed (see Fig. 3(b)) for which the following values have been found: Zs = 170 Ω, Θ1 = 32°, Θ2 = 38°, C = 13 pF.

III. Broadband Balun Circuit Realization

To experimentally verify the presented concept, a coupled line section has been designed in a coupled-line geometry shown in Fig. 4, for which h_1 = 0.152 mm, ε_{r1} = 3.38, h_2 = 0.04 mm, ε_{r2} = 3.38, h_3 =1.524 mm, ε_{r3} = 3.38 and w_1 = 0.92 mm, w_2 = 3.71 mm. The per-unit-length parameters, listed in Table I, and the dimensions of the strips have been found numerically using Linpar software [9].



(a) (b)

Fig. 3. Lumped element equivalent circuit of an LH transmission-line section (a) and its semi-distributed version (b).

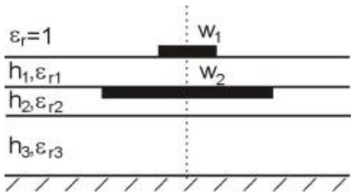
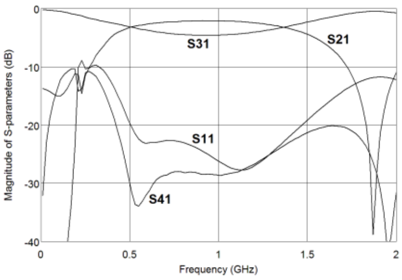


Fig. 4. Cross-section of the dielectric structure used for the design of the broadband balun circuit.

TABLE I: Parameters of the Coupled-Line Section for Which R = 1.43, Designed in the Structure Shown in Fig. 4, Having h_1 = 0.152 mm, ε_{r1} = 3.38, h_2 = 0.04 mm, ε_{r2} = 3.38, h_3 =1.524 mm, ε_{r3} = 3.38 and w_1 = 0.92 mm, w_2 = 3.71 mm

Parameter	Value	Parameter	Value
$C11$ [pF/m]	224.9	kC	0.81
$C22$ [pF/m]	335.2	k	0.804
Cm [pF/m]	222.3	ZT1 [Ω]	50
$C1$ [pF/m]	2.6	ZT2,3 [Ω]	35
$C2$ [pF/m]	112.9	ZT4 [Ω]	24.5
$L11$ [nH/m]	395.7	ZL1 [Ω]	41.95
$L22$ [nH/m]	271.3	ZL2 [Ω]	28.45
Lm [nH/m]	261.5	ε_{effc}	2.972
kL	0.789	$\varepsilon_{eff\pi}$	2.759

To verify the properties of the proposed balun circuit, an electromagnetic calculation has been made in which the designed coupled-line section in conjunction with LH and RH transmission-line sections have been analyzed. The obtained S parameters are presented in Fig. 5. One can notice a very good agreement between the circuit and electromagnetic analysis in terms of both amplitude and phase response. Finally, the proposed circuit has been fabricated and measured with the VNA under 50 Ω terminating impedances at all ports. The obtained results have been recalculated to the proper terminating impedances at each port as denoted schematically in Fig. 1. The measurement results have been presented in Fig. 6, which fully confirm the results of both theoretical and electromagnetic analyses.



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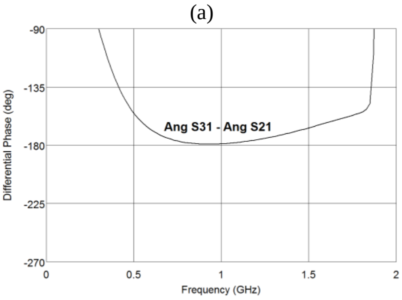
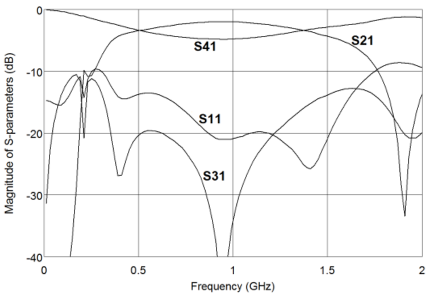
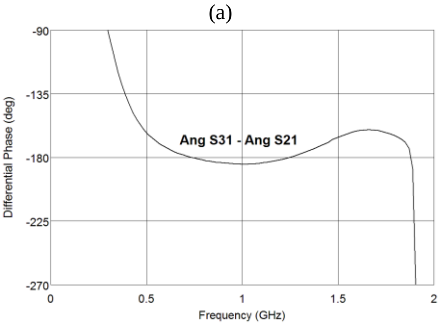


(b)

Fig. 5. Magnitude of *S* parameters (a), and the differential phase (b) of the designed broadband balun circuit. Results of electromagnetic calculations.



(a)



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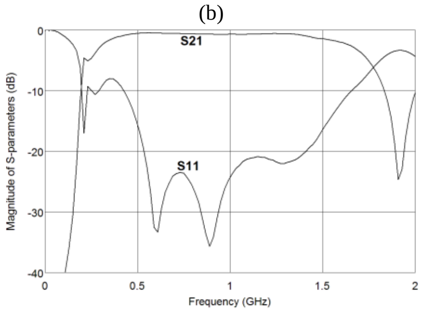

(c)

Fig. 6. Measured magnitude of *S* parameters (a), the differential phase (b) of the designed broadband balun circuit and the *S* parameters of its back-to-back connection (c).

From the measurement result of a single balun circuit, the properties of its back-to-back connection have been found, and the results are presented in Fig. 6(c). As it is seen the proposed circuit operates in over-an-octave frequency range with relatively low insertion losses and good impedance match. The photograph of the manufactured circuit is presented in Fig. 7.

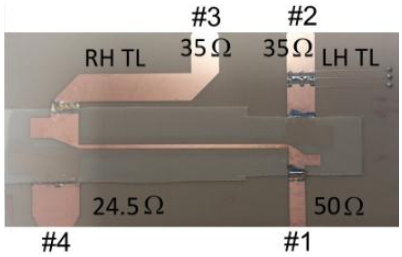

Fig. 7. A photo of the manufactured balun as a connection of the impedance transforming directional coupler with 45°-long LH and RH transmission-line sections.

IV. Conclusion

In this paper, a novel approach to the design of the balun circuit has been presented in which an impedance transforming coupled-line section has been used in conjunction with an LH/RH differential phase shifter. The proposed circuit allows for realization of baluns offering flexibility of impedance transformation ratio selection in a wide impedance range. The circuit features broadband frequency response exceeding one octave. The theoretical analyses have been confirmed with the measurement results of the designed balun.

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