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# Analysis and Design of Lumped Element Marchand Baluns

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**Abstract**—In this paper a novel design procedure for lumped element Marchand baluns is proposed. An analysis is performed on the balun structure in order to determine the conditions for ideal balun performance in terms of the lumped element values. The analysis is verified by two broadband designs centered around 22.75 GHz and differing only in terms of their impedance transformation ratio. EM simulation results on our proposed lumped element Marchand balun structure predicts an insertion loss of 4 dB and return loss of 40 dB at the design frequency of 22.75 GHz. The amplitude and phase imbalance is predicted to be better than 1 dB and  $6^\circ$ , respectively obtained over a wide 15 GHz bandwidth.

## I. INTRODUCTION

Baluns are key components in balanced mixers, push-pull amplifiers, and antennas. They provide conversion between an unbalanced input signal and balanced output signals. Generally speaking, baluns can be classified into active and passive topologies. Active baluns are attractive for MMIC applications due to their compact sizes [1]. They do, however, limit the dynamic range of the balanced mixer or amplifier circuit. Passive baluns can be divided into lumped element [2] and distributed baluns [3]. The conventional Marchand balun employing two quarter wave-length coupled line sections is perhaps the most attractive topology due to its wideband performance. The main disadvantages of the conventional Marchand balun is its large size increasing the fabrication cost for MMIC application except at the highest mm-wave frequencies. Several techniques to reduced the size of the Marchand balun has been proposed [4]-[5]. Commonly a lumped-distributed technique is employed in order to reduce the size of the coupled line sections. Another more compact solution is to employ interwound spiral transformer-type lumped element baluns. Unfortunately, clear guidelines for designing these lumped element Marchand baluns are not available. Therefore these balun must be designed using parametric analysis based on electromagnetic simulations. A clear design procedure would clearly be beneficial for lumped elements Marchand baluns.

In this paper we present an analysis on a lumped element Marchand balun. Expressions for the lumped element values leading to equivalence with the conventional Marchand balun at the design frequency is presented. The design procedure gives the requirements on the inductance, the mutual inductive coupling, and the capacitive coupling for the interwound spiral transformer. The bound between the coupling capacitors and external shunting capacitors is given. Two broadband designs centered at 22.75 GHz illustrates the design procedure for different impedance transformation ratios. A lumped element balun structure designed for a 1:1 impedance transformation

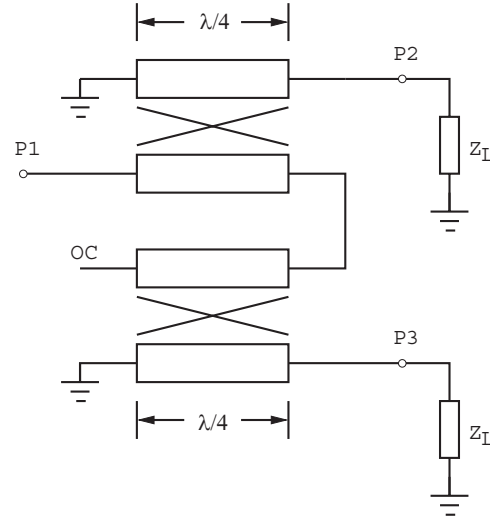


Fig. 1. Conventional Marchand balun.

ratio is currently being implemented in an InP DHBT technology. The preliminary results based on EM simulation will be reported. Experimental results should be available at the time of the conference.

## II. ANALYSIS OF MARCHAND BALUN

The conventional Marchand balun is shown in Fig. 1. It provides balanced signals across the load impedances  $Z_L$  at the two output ports ( $P2$  and  $P3$ ) when driven from an unbalanced signal at the input port ( $P1$ ). In general the load impedances are different from the driving impedance  $Z_0$  at the input port. The ideal balun operation can be characterized in terms of the S-parameters

$$S_{11} = 0 \quad (1)$$

$$S_{21} = -S_{31}. \quad (2)$$

The conventional Marchand balun fulfills these S-parameters conditions over a very large bandwidth. It has recently been shown that the condition in (2) only can be fulfilled if the even-mode circuit of the balun have a zero in the transmission [6]. This condition is enforced in our balun design procedure. The first order equivalent circuit of the spiral transformer-type Marchand balun is shown in Fig. 2 [7]. In order to find the conditions for equivalence between the lumped element representation in Fig. 2 and the conventional Marchand balun we propose to employ an even/odd mode analysis on each coupled line section. Considering first the even mode circuit of a single  $\lambda/4$  coupled line section as shown in Fig. 3a).

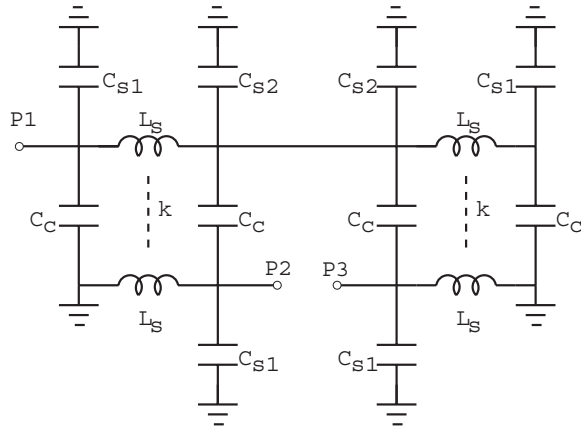


Fig. 2. Lumped element Marchand Balun.

This can be represented with a  $\lambda/4$  transmission line with characteristic impedance  $Z_{oe}$ . The lumped element equivalent circuit shown in Fig. 3b) can represent this transmission line if

$$\omega L_s(1+k) = Z_{oe} \quad (3)$$

$$\omega^2 L_s(1+k)C_s = 1 \quad (4)$$

where  $\omega$  is the design frequency in rad/s and  $C_s = C_{s1} = C_{s2}$  have been assumed. Similar the odd mode circuit of a single  $\lambda/4$  coupled line section shown in Fig. 4a) can be represented with the lumped element equivalent circuit shown in Fig. 4b) if

$$\omega L_s(1-k) = Z_{oo} \quad (5)$$

$$\omega^2 L_s(1-k)(C_s + 2C_c) = 1 \quad (6)$$

where  $Z_{oo}$  is the characteristic impedance of the  $\lambda/4$  coupled line section under odd-mode excitation. If (4) and (6) are fulfilled then the bound between the coupling capacitance  $C_c$

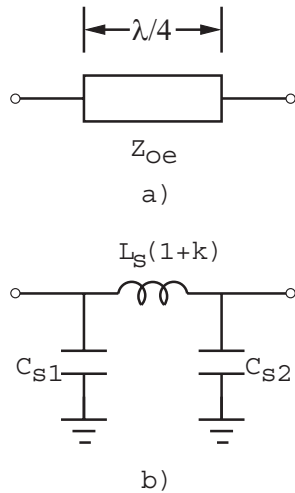


Fig. 3. a) Even-mode circuit of quarter-wavelength coupled transmission lines. b) Lumped equivalent circuit model.

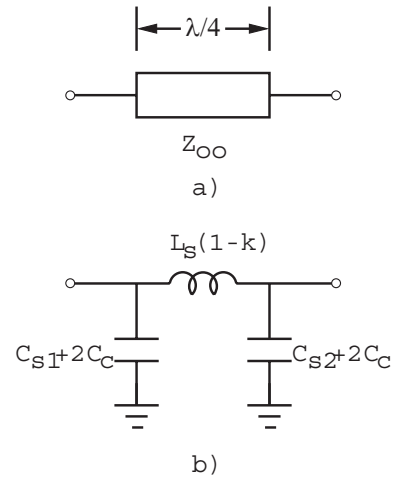


Fig. 4. a) Odd-mode circuit of quarter-wavelength coupled transmission lines. b) Lumped equivalent circuit model.

and the shunt capacitance  $C_s$  is given by

$$C_s = \frac{C_c - kC_c}{k} \quad (7)$$

It can be shown that this is exactly the bound leading to zero transmission at all frequencies in the even mode circuit of the lumped element Marchand balun in Fig. 2. This means that the amplitude and phase imbalance will be zero at all frequencies if (7) is fulfilled, at least in theory.

### III. DESIGN PROCEDURE

Turning now our attention to the design procedure the first point is to determine the even and odd-mode characteristic impedance for the coupled line section. For a given impedance transformation ratio the coupling factor  $C$  can be determined as

$$C = \frac{1}{\sqrt{(2Z_L/Z_o + 1)}} \quad (8)$$

from which the even and odd-mode impedances is easily determined [3]. From (3) and (5) we determine the self-inductance  $L_s$  and mutual inductive coupling  $k$  as

$$L_s = \frac{Z_{oe} + Z_{oo}}{2\omega} \quad (9)$$

and

$$k = \frac{Z_{oe} - Z_{oo}}{2\omega L_s} \quad (10)$$

respectively. From (3) and (4) the shunt capacitors  $C_{s1}$  and  $C_{s2}$  are determined

$$C_{s1} = C_{s2} = C_s = \frac{1}{\omega Z_{oe}} \quad (11)$$

where identical capacitor values are assumed. Finally the capacitive coupling  $C_c$  can be determined from (5) and (6) as

$$C_c = \frac{1}{2\omega Z_{oo}} - 0.5C_s \quad (12)$$

	1 : 1 Balun	1 : 2 Balun
$Z_{oe}$ [ $\Omega$ ]	96.5	80.1
$Z_{oo}$ [ $\Omega$ ]	25.9	31.2
$L_s$ [nH]	0.428	0.389
$k$	0.577	0.439
$C_s$ [fF]	72.5	87.3
$C_c$ [fF]	98.8	68.5

TABLE I  
VALUES FOR LUMPED ELEMENT MARCHAND BALUN WITH 1:1 AND 1:2  
IMPEDANCE TRANSFORMATION RATIO.

once  $C_s$  is known. In order to verify the analysis and the proposed design procedure two lumped element Marchand baluns have been designed at a center frequency of 22.75 GHz. The design frequency is chosen to correspond with the center frequency of the LO signal for a 43 GHz balanced sub-harmonic mixer with a 2.5 GHz IF frequency. The designs differs in terms of their impedance transformation ratio. For the first design a 1:1 impedance transformation ratio is chosen. For the second design a 1:2 impedance transformation ratio is chosen as this more realistically correspond to the impedance levels experience in a balanced sub-harmonic mixer circuit. Table I gives the element values for the two designs. The calculated even and odd-mode characteristic impedances for each coupled line section is also given. The simulated results for the lumped element balun using ideal components are shown in Fig. 5 and 6. The results demonstrates half power division capabilities for both designs. The balun design with 1:1 impedance transformation ratio shows a 19.1 GHz bandwidth while the bandwidth of the other balun design is slightly lower. The return loss at the design frequency is better than 65 dB. Because of the bound which is enforced between the coupling capacitance  $C_c$  and shunting capacitance  $C_s$  in our design procedure the amplitude and phase imbalance is zero at all frequencies. This is illustrated in Fig. 6 for the phase shift between the input port and the two output ports.

#### IV. RESULTS AND DISCUSSION

In this section the layout of the lumped element Marchand balun design with 1:1 transformation ratio is described. The first point is to design a spiral transformer for the calculated

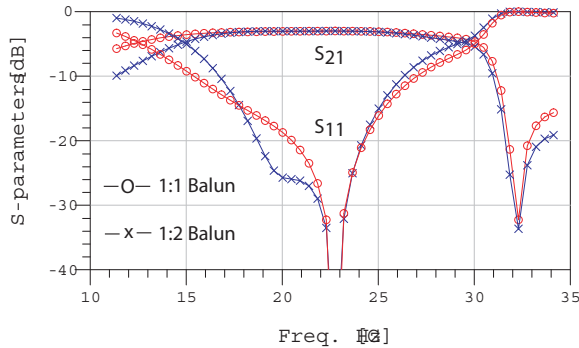


Fig. 5. Simulated S-parameters versus frequency of lumped element Marchand balun.

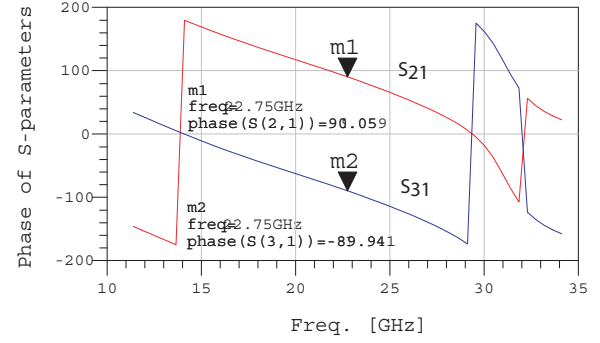


Fig. 6. Simulated phase of  $S_{21}$  and  $S_{31}$  for lumped element Marchand balun (1 : 1 Balun).

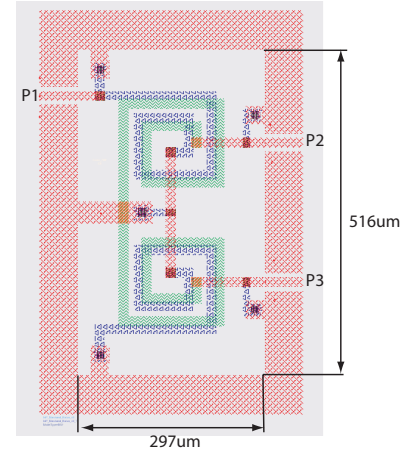


Fig. 7. Layout of spiral transformer-type balun.

self-inductance, mutual inductive coupling, and coupling capacitance as given in Table. 1. The used InP technology offers three metals layers separated by thin polyimide dielectrics. To obtain the correct spiral transformer performance the lower and upper metal layers are applied in a partly overlapped broadside coupling configuration. MIM capacitors are added to the layout in order to obtain the values for  $C_s$  given in table 1. In particular the capacitance  $C_{s2}$  should be carefully selected in order to fulfill the bound with the coupling capacitor  $C_c$  previously stated in (7). A view of the proposed layout is shown in Fig. 7. A very compact size of  $291\mu m \times 516\mu m$  is achieved. EM simulations have been performed on the proposed lumped element Marchand balun structure using Momentum in ADS 2005. The simulated results are shown in Fig. 8 and Fig. 9. An insertion loss of 4 dB and a return loss of 40 dB is predicted from the EM simulation at the design frequency of 22.75 GHz. The additional loss of 1 dB stems mainly from the conductor losses in the spiral transformer which can be reduced by using wider lines. The amplitude and phase imbalance is 0.02 dB and  $2^\circ$  at the design frequency and better than 1 dB and  $6^\circ$ , respectively over the frequency range from 15 GHz to 30 GHz.

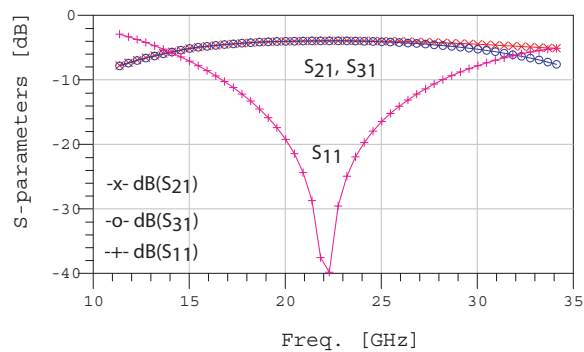


Fig. 8. EM simulation results of lumped element Marchand balun.

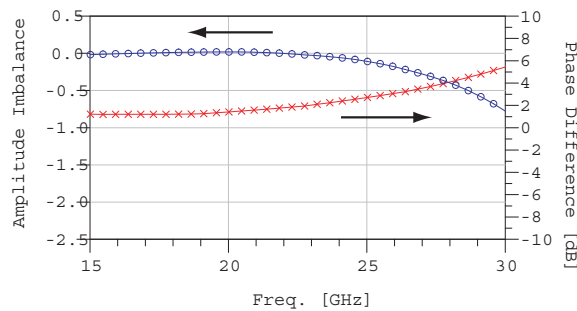


Fig. 9. EM simulated amplitude imbalance and phase imbalance for lumped element Marchand balun.

## V. CONCLUSION

We have reported on a novel design procedure for lumped element Marchand baluns. The design procedure follows from an analysis of the lumped element Marchand balun. A bound between the coupling capacitance and the shunting capacitance which eliminates any amplitude and phase imbalances in the lumped element balun design was given. The analysis and design procedure was verified on two designs with a 1:1 and a 1:2 impedance transformation ratio. The simulated results showed the expected half power dividing capability over a wide bandwidth for both balun design. The lumped element balun using ideal components showed zero amplitude and phase imbalances as theoretically expected. EM simulation performed on our proposed lumped element Marchand balun structure predicted an insertion loss of 4 dB and return loss of 40 dB. The amplitude and phase imbalance was predicted to be better than 1 dB and  $6^\circ$ , respectively over the frequency range from 15 GHz to 30 GHz.

## ACKNOWLEDGMENT

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