A novel model for a planar wideband Marchand balun*

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Abstract: A new lumped element model for conventional Marchand baluns is presented. Analyzed by the even- and odd-mode method, the equivalent equations are derived for $\lambda/4$ coupled lines. Based on the proposed 5th-order lumped equivalent circuit for $\lambda/4$ coupled lines, the self-inductance, mutual inductive coupling and the capacitance can be calculated according to the even- and odd-mode characteristic impedance, therefore, the model parameters of the balun can be easily gained from the derived equations. To verify the model, a GaAs monolithic wideband Marchand balun was implemented and tested. The EM simulation and experimental results show a good agreement with the model simulation. This model is available in a wide frequency range and makes the design procedure of the Marchand balun faster and easier.

Key words: model; wideband; coupled line; MMIC; Marchand balun
DOI: 10.1088/1674-4926/32/11/115010 **EEACC:** 2570

1. Introduction

In many wireless communication systems, baluns providing a transformation between a balanced structure and an unbalanced one are key components in balanced circuit topologies such as double balanced mixers, push–pull amplifiers and frequency doublers[1−3]. Various types of baluns have been reported for applications in monolithic microwave integrated circuits (MMICs)[4−6]. Among them, the planar version of the Marchand balun is perhaps one of the most popular choices for millimeter-wave designs because of its design simplicity and wideband performance.

A planar Marchand balun consists of two sections of quarter-wave coupled line and each section has one terminal grounded[7]. As a necessary tool for circuit design, the equivalent circuit models and analytically derived scattering parameters for the synthesis of baluns have been reported[8−11]. However, these reported models are based on transmission lines and have complicated calculation processes, which are hard to simulate using general SPICE tools. A clear design procedure for the lumped element Marchand balun has also been reported[12], however, this proposed 2nd-order equivalent circuit can not provide a precise lumped element model for wideband baluns because of the distributed characteristics of the transmission line.

In this paper, a novel lumped element model for the conventional planar Marchand balun is presented based on a 5th-order equivalent circuit. Expressions for the lumped element values of the balun in terms of the even and odd modes of coupled-line are derived, therefore, the values of the inductance, the mutual inductive coupling and the capacitive coupling can be calculated easily. In order to verify the model, a monolithic millimeter-wave Marchand balun has been designed by using Win's GaAs process, the balun is simulated by using the proposed model and HFSS (Ansoft), respectively. Finally, the designed balun is tapped out and tested.

2. Planar Marchand balun modeling

2.1. Balun analysis

A conventional planar Marchand balun consists of two symmetrical quarter-wave coupled lines at the centre frequency of operation. As shown in Fig. 1, the characteristic impedance and coupling factor of each parallel-line couplers are denoted as Z_0 and k, respectively. In general, the load impedances Z_L are different from the source impedance Z_s.

For symmetric baluns, the scattering matrix of the balun can be derived from the scattering matrix of two identical cou-

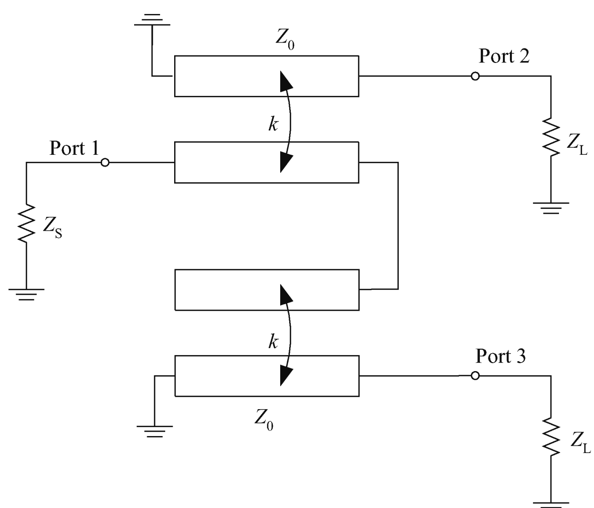

Fig. 1. Conventional Marchand balun.

* Project supported by the Start-Up Fund for Senior Professional Research in Jiangsu University, China (No. 11JDG057) and the Natural Science Fund for Colleges and Universities in Jiangsu Province, China (No. 10KJB510002).
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Received 22 May 2011, revised manuscript received 29 June 2011

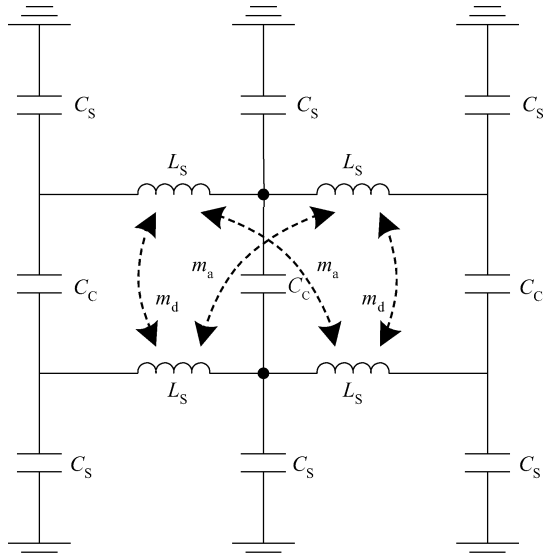

Fig. 2. Lumped element equivalent circuit of a coupled line.

plers. To achieve optimum power transfer of –3 dB to each port, the S-parameter should be[9]

$$|S_{21}| = |S_{31}| = \frac{1}{\sqrt{2}}. \tag{1}$$

The coupling coefficient k is the critical parameter because it not only decides the S-parameters of the Marchand balun, but also influences the parameters of the lumped element model. In the lumped element model, the values of the inductances and capacitances can be calculated by the even- and odd-mode impedances of the coupled line, which are dependent on k as follows:

$$Z_{0e} = Z_0\sqrt{\frac{1+k}{1-k}}, \tag{2}$$

$$Z_{0o} = Z_0\sqrt{\frac{1-k}{1+k}}, \tag{3}$$

where Z_{0e} and Z_{0o} are even and odd mode impedances of the coupled line, respectively.

2.2. Coupled line modeling

In order to model the Marchand balun, the coupled lines should be analyzed first. We proposed a 5th-order equivalent circuit of the coupled line as shown in Fig. 2. Here m_d is the mutual inductive coupling coefficient between two directly opposite inductances L_s, m_a is the one between two diagonally opposite inductances. In the model, m_d is the main factor for coupling effect and m_a is only about one twentieth of m_d.

Using an even/odd mode analysis on each coupled line section, the conditions for equivalence between the lumped element circuit in Fig. 2 and the coupled line can be derived. Figure 3 shows the lumped equivalent circuit model for a single $\lambda/4$ coupled line section with characteristic impedance Z_{0e}.

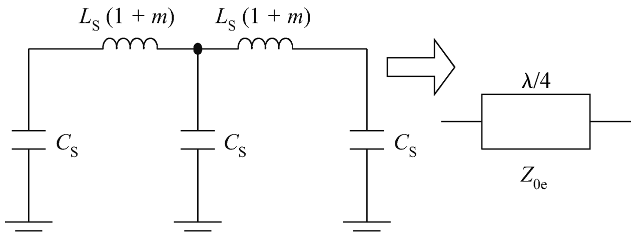

Fig. 3. Lumped equivalent circuit for even mode circuit of a $\lambda/4$ coupled line.

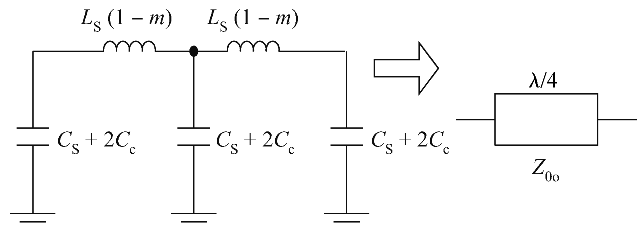

Fig. 4. Lumped equivalent circuit for an odd mode circuit of $\lambda/4$ coupled line.

For a $\lambda/4$ transmission line, the input impedance is zero when the line is opened, so we can derive the resolution as

$$\omega^2 L_S C_S(1+m) = \frac{3-\sqrt{5}}{2} = 0.38, \tag{4}$$

where ω is the design frequency in rad/s and $m = m_d + m_a$, according to the definition of the characteristic impedance of the transmission line, the even mode impedance is:

$$Z_{0e} = \sqrt{\frac{L_S(1+m)}{C_S}}. \tag{5}$$

Similarly, the odd mode equivalent circuit of a single $\lambda/4$ coupled line is shown in Fig. 4.

For odd mode stimulation, the coupled line can be presented as two symmetric lines with capacitance $2C_C$ linking to ground, so the equivalent capacitance to ground for single line is $C_S + 2C_C$, the equivalent inductance for single line is $L_S(1-m)$. As shown in Fig. 4, to make this circuit has the same behaviour as a $\lambda/4$ line, the model parameters should meet the conditions as the follows:

$$\omega^2 L_S(C_S + 2C_c)(1-m) = \frac{3-\sqrt{5}}{2} = 0.38, \tag{6}$$

$$Z_{0o} = \sqrt{\frac{L_S(1-m)}{C_S+2C_c}}, \tag{7}$$

where Z_{0o} is the characteristic impedance of the $\lambda/4$ coupled line section with odd mode excitation.

For a given coupling coefficient k, the even- and odd-mode characteristic impedances are calculated by means of Eqs. (2) and (3). Thus the parameters of the lumped element model can

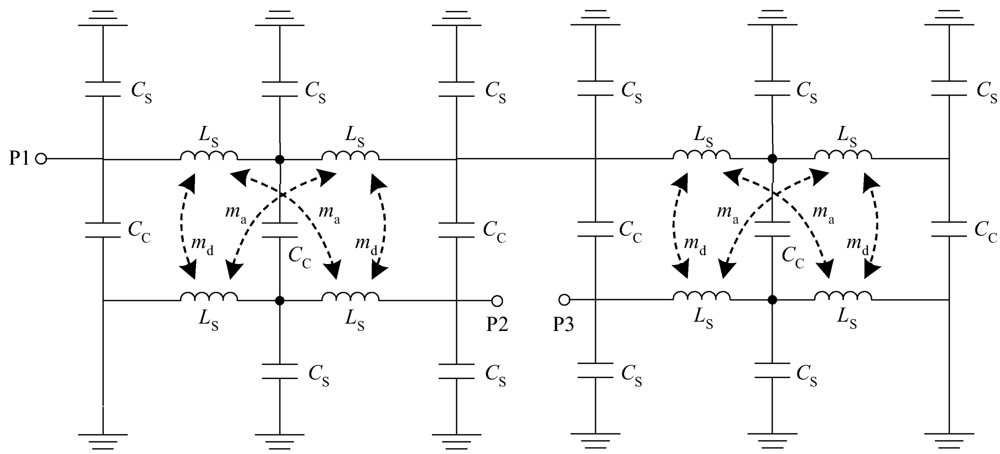

Fig. 5. Lumped element equivalent circuit of a Marchand balun.

Table 1. Design & model parameters for Baluns.

Parameter	Balun1 (two coupled line)
Z_{0e}	115.6 Ω
Z_{0o}	28.7 Ω
L_s	0.21 nH
C_s	25 fF
C_c	37 fF
m	0.596
Line width	20 μm
Line space	8 μm

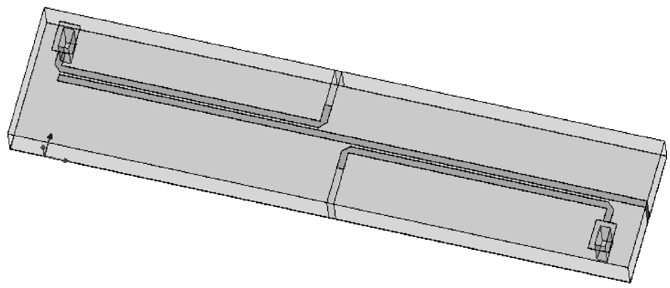

Fig. 6. 3-D MMIC Marchand balun structure.

be easily determined from Eqs. (4)–(7). Figure 5 shows the lumped element equivalent circuit of a Marchand balun.

3. Model verification

3.1. Model simulation

To verify the proposed model, a millimeter-wave wideband Marchand balun is designed by using Win's 0.15-μm pHEMT GaAs process. The balun works at the center frequency of 33 GHz and its bandwidth is over 20 GHz. Though a higher coupling coefficient results in wider bandwidth of the Marchand balun, the coupling coefficient is not selected as high as possible in actual design. It has been proved that the insertion loss will be decreased at the center frequency if the coupling coefficient is greater than 0.63[10]. In this design, the coupling coefficient $k = 0.6$ is selected for the purpose of a flat frequency response. Table 1 gives the calculated even- and odd-mode characteristic impedances and the lumped element values for each coupled line section.

In terms of the used GaAs process design kit (PDK), the coupled line with the given parameters in Table 1 can be easily designed by using ADS of Agilent. Finally, the physical dimension parameters of the Marchand balun are synthesized as follows: $W = 20$ μm, $S = 8$ μm, $L = 800$ μm.

The balun was simulated by the full wave electromagnetic simulator HFSS. Figure 6 shows the proposed 3-D MMIC Marchand balun drawn by HFSS. The simulated insertion losses and phase imbalance are shown in Figs. 7 and 8, which have a comparison for HFSS and model respectively.

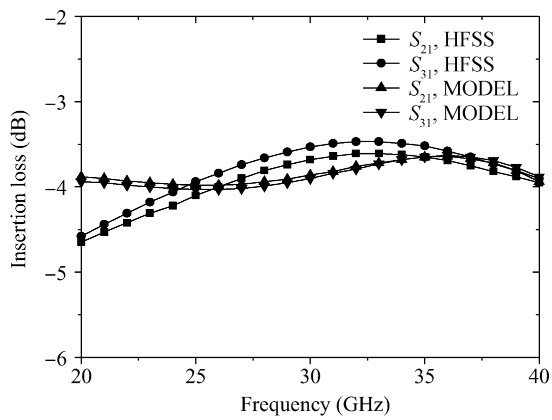

Fig. 7. Simulated insertion losses of the balun.

As shown in Fig. 7, the insertion loss is illustrated by S_{21} and S_{31} of the balun. From 26 to 40 GHz, S_{21} and S_{31} have the same tendency and show closely, the results from the lumped element model are close to that of HFSS. The difference between them will increase slightly when the frequency decreases below 26 GHz. Because the model parameters are calculated at centre frequency of 33 GHz, the model error will increase as the frequency deviate from 33 GHz. In Fig. 8, the phase difference between tow output ports is near 180 degree, compared with HFSS, the lumped model has good consistency.

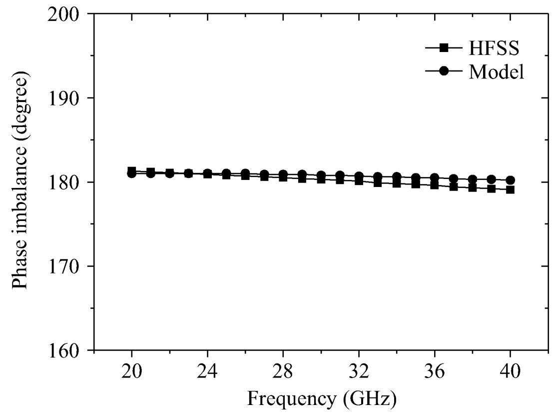

Fig. 8. Simulated phase imbalance of the balun.

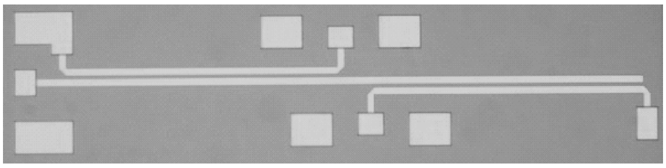

Fig. 9. Microphotograph of fabricated balun.

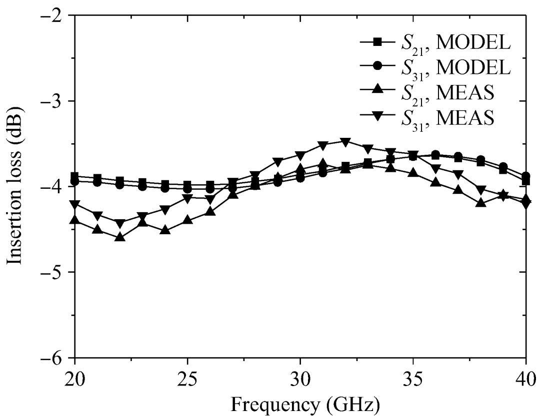

Fig. 10. Measured and simulated insertion losses of the balun.

3.2. Experiment

The designed Marchand balun was fabricated on the PHEMT MMIC process offered by the WIN Semiconductor in Taiwan. The substrate is thinned down to 100 μm thick and the top-metal layer is 2 μm thick. Figure 9 shows the chip photograph of the designed Marchand balun. The chip size is 0.3×1.8 mm^2.

The balun was measured via on-wafer probing through ground-signal-ground RF probes. At first, the losses of the probes and cables were calibrated by means of Agilent E8363B network analyser. Then, the S-parameters of the balun were measured. The simulation and measurement results are shown in Fig. 10. The lumped element model is simulated by means of ADS, as the figure shows, the insertion loss is 3.6–4.1 dB in the range of 20–40 GHz. Compared to the model simulation and the measured results, the model insertion losses are very close to measured ones and their difference are less than 0.5 dB. The model error increases slightly when the frequency goes far from the center frequency. The simulated and measured phase imbalances of the balun are plotted in Fig. 11. The lumped element model shows a good agreement with the measured results over the frequency range from 20 to 40 GHz.

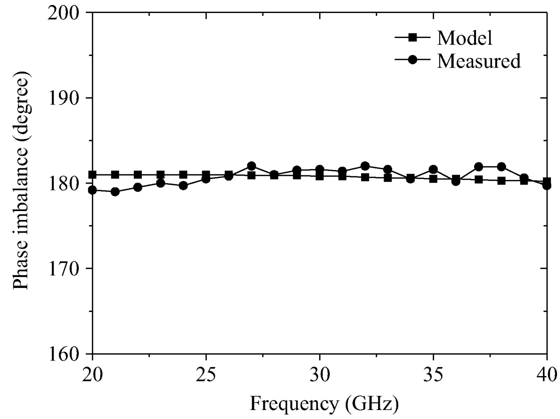

Fig. 11. Measured and simulated phase imbalance of the balun.

4. Conclusion

A new lumped element model for a coupled line and a Marchand balun has been proposed. The model uses even- and odd-mode analytical method to derive the equations for a $\lambda/4$ coupled transmission line. Therefore, the lumped element parameters can be calculated fast and easily. The model has been successfully used for the synthesis of a monolithic broadband Marchand balun. The EM simulation and experimental results show a good agreement with the model simulation. The model is useful in a broad frequency range and can predict the performance of the Marchand balun accurately. The designed Marchan balun achieves good amplitude imbalance and phase imbalance over the frequency range from 20 to 40 GHz.

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