Analysis of tunable Marchand baluns

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Abstract — The paper tackles the issue of designing tunable Marchand baluns and provides an insight on available approaches for integrating the structure in a semiconductor process. Limitation of the approach and possible solutions are also discussed. The analysis is applied to a Marchand balun fabricated in IBM 8HP SiGe process to demonstrate the feasibility of the approach. A mix of measured and simulated data is used to support the analysis at Q band. State-of-the-art performance is achieved.

Index Terms — Millimeter wave integrated circuits, Passive circuits, Tunable circuits and devices, Linear circuits, Silicon germanium, Integrated circuit modeling.

I. INTRODUCTION

Baluns have become an important component of modern Silicon designs as they enable the transformation of two out-of-phase single-ended signals into differential form. Among the possible approaches [1], Marchand baluns [2] have been demonstrated to achieve very good performance at mm-wave frequencies in integrated form [3]–[5] despite the considerable Silicon substrate loss.

Baluns are passive and reciprocal 3-port networks with port 1 being the single ended port; and port 2 and 3 being the differential signal. Marchand baluns, in particular, can be considered as consisting of a set of 2 coupled lines connected back-to-back. Fig. 1 shows that the proper connection of the available nodes to form a Marchand balun is not unique. However, the additional port P4 must be AC-grounded to support the differential-to-single ended transformation, even though it may be used as a DC connection depending of the particular application of the balun. For example, a differential amplifier can be connected to P1-P2 with P4 delivering the proper bias.

The RF performance of the balun is characterized by 2 sets of quantities, normally defined in terms of single-ended scattering parameters $S_{ij}$:

1) the magnitude $M_{imb}$ and phase $\phi_{imb}$ imbalance

$$M_{imb} = \left| \frac{S_{31}}{S_{21}} \right|$$

$$\phi_{imb} = 180^\circ - \frac{S_{31}}{S_{21}}; \quad \text{and}$$

2) the insertion loss $\alpha$

$$\alpha = |S_{31}|^2 + |S_{21}|^2$$

The insertion loss definition is not unique [4], [6] and expressions based on mixed signal signals can also be found in the public domain [1]. When $\alpha$ is expressed in dB, the insertion loss is usually reported as a positive number – the larger the number, the larger the loss.

The requirement that port P4 is AC-grounded for the Marchand balun to operate imposes an inherent bandwidth constraint to keep magnitude and phase imbalance within a small range of values. However, it also presents an opportunity to make the balun tunable by setting the AC ground at the frequency of interest. Recent work [3] opted for adding a susceptive element between the coupled lines and ground with interesting results. Instead, this paper will provide a detailed analysis on how to exploit port P4 to make a Marchand balun tunable and will present measurements to validate the analysis.

II. ANALYSIS OUTLINE

The analysis begins with defining the scattering parameter of an individual ideal coupled line with coupling $C$:

$$S_{\text{CLIN}} = \begin{bmatrix}
0 & C & -jK & 0 \\
C & 0 & 0 & -jK \\
-jK & 0 & 0 & C \\
0 & -jK & C & 0 
\end{bmatrix}$$

where $K = \sqrt{1 - C^2}$. Then, using scattering parameter based analysis [7], it is possible to write a $4 \times 4$ scattering matrix:

1Unless explicitly indicated otherwise, scattering parameters $S_{ij}$ are to be considered single-ended.
Fig. 2. The Marchand balun in IBM 8HP SiGe process. The launch structures are clearly visible. The GSG pads on the lower right allow access to the single-end port P1; the top GSG pads allow access to P4. Ports throughout the paper are intended to be at the reference planes as defined in Fig. (1) obtained after de-embedding of the launch structures.

One port of a coupled line network is loaded by an AC-ground when obtaining a wave exiting port 4 of the balun towards the load \( P_4 \). Equation (5) describes the fact that a wave incident into port 4 of the balun is commonly indicated as \( a_{P4} \). In terms of scattering parameters, \( \Gamma_{P4} = b_{P4} a_{P4} \) (5)

where \( a_{P4} \) and \( b_{P4} \) are column vectors of the incident and reflected waves \( a_{P4} \) and \( b_{P4} \) respectively. Note from Fig. 1 that one port of a coupled line network is loaded by an open circuit – load that must be properly accounted for when obtaining \( S_F \).

The matrix \( S_F \) in (4.2) has been partitioned in 4 sub-matrices of different size as indicated by their subscripts. The partition allows to write a suitable matrix form when considering that port \( P_4 \) may be available for tuning through a load that shunts \( P_4 \) to ground through a susceptance \( B_{P4} \). In terms of scattering parameters, \( \Gamma_{P4} = b_{P4} a_{P4} \) (5)

where \( a_{P4} = \Gamma_{P4} b_{P4} \) and \( b_{P4} = S_F a_{P4} \) (4.1)

The imbalance ratio (1) for Fig. 1 in complex form is found to be:

\[
\frac{S_{31}}{S_{21}} = -1 + \frac{2C^2}{1 + jB_{P4} Z_o} \tag{7}
\]

where \( Z_o \) is the normalization impedance at port P1 and \( P_4 \); and \( Z_o/2 \) is the normalization impedance at port P2 and P3. As expected, the balun performs ideally if the susceptance \( B_{P4} \) is an ideal short to ground at port \( P_4 \). In other words, \( M_{imb} = 1 \) and \( \phi_{imb} = 0 \) for \( B_{P4} \rightarrow +\infty \).

III. DISCUSSION

Expression (7) is valid for the frequency \( f_o \) that makes the electrical length of each coupled line equal to \( \pi/2 \) or alternatively, its length \( l \) equal to \( \lambda/4 \). When this occurs, then \( S_{CLIN} \) is ideally expressed by (3). Within
the assumptions of the procedure described so far, $B_{P4}$ can only degrade the balun’s performance [3] as (7) shows. However, perfect match at each port may not be achieved and other discrepancies from the ideal matrix (3) may take place. Consequently, the susceptance $b_{P4}$ is a useful parameter that can be used to tune the performance of the Marchand balun.

Tunability becomes more and more challenging to implement in integrated form as the frequency becomes higher and higher. While varactors have reasonable performance in the low GHz region, losses may be overwhelmingly large at mm-wave frequency. Nevertheless, the analysis of Section II may indicate a useful direction for the design of a tunable balun.

A Marchand balun design at Q band has recently been implemented in IBM’s 8HP process [8]. A picture of the balun is shown in Fig. 2. The balun is based on the basic network shown in Fig. (1b). In order to provide an AC ground at port P4, a large capacitor should be placed at the T junction where the line from port 4 (top pads in Fig. 2) meets the connection between spirals. However, the physical size of the capacitor may not allow to place it at the T junction. If the capacitor is further away, the metal line connecting capacitor to T junction will show distributed effect, causing $\Gamma_{P4}$ to shift towards +1 from the ideal value of -1. A suitable combination of metal line length and an additional small capacitor $C_N$ will provide the required shunt connection at the T junction.

This approach aiming at tuning the balun’s performance has been demonstrated with a mixture of Agilent’s Momentum based simulations paired with measurements of 4 different tiles of the Marchand balun of Fig. 2. The balun is designed on the top metal level and proper screening of the substrate was accounted for to minimize the bulk loss.

Fig. (2) shows the launch structures consisting of pads and access lines stemming from the signal pad. The launch structures are required components of the layout to facilitate the on-wafer characterization of the balun. Additional calibration structures were fabricated on the same Silicon tiles along with the balun. Two launch structures were characterized individually to de-embed their contribution from the measured scattering parameters.

A 4-port Agilent VNA has been calibrated with an “unknown through” up to the probe tips in the Q band region. The “unknown through” was manufactured in-house as it is not a critical component of the calibration procedure and availability at the time was an issue. Each port’s reference impedance during measurement is $50 \, \Omega$. However, the balun operates with a reference impedance of $25 \, \Omega$ for port P2 and P3 and of $50 \, \Omega$ for P1 and P4. This explains why the measured $S_{22}$ are off-centered.

The line with the marker in Fig. 3 shows the effect of the combination “small capacitor $C_N$ + line + large capacitor” applied at the balun’s T-junction as described above: the susceptance provided at that junction is slightly off the Smith chart value -1 because the balun is not ideal and (7) does not capture the actual non-idealities. However, the performance of the tuned balun is excellent and comparable to state-of-the-art results as Table I shows.

Fig. 4 and Fig. 5 show the measured imbalance before and after tuning as defined in (1) in the range 30−50 (GHz). The proper tuning of the balun’s T-junction allows very good performance over a wide range (more than $\pm10\%$) for $M_{imb}$ to be within $\pm1$ (dB) and for $\phi_{imb}$ to be within $\pm10$ (deg).

Fig. 6 shows the performance of the balun in terms of mixed-mode scattering parameters [9]. The differential and common mode are associated with ports P2 and P3 and P1 is the single-ended port. The plots show that P2-P3 are well matched to a differential signal, the common mode
TABLE I
BALUN PERFORMANCE AGAINST RECENT PUBLISHED RESULTS.

<table>
<thead>
<tr>
<th>Ref.</th>
<th>$f_0$ (GHz)</th>
<th>Area (mm$^2$)</th>
<th>$M_{imb}$ (dB)</th>
<th>$\phi_{imb}$ (deg)</th>
<th>$\alpha_{dif}$ (dB)</th>
<th>Technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>This paper</td>
<td>40.0</td>
<td>0.197</td>
<td>+/-1.0</td>
<td>+8.0/-10.0</td>
<td>&lt; 2.5</td>
<td>180nm SiGe BiCMOS 1 layer balun</td>
</tr>
<tr>
<td>[1]</td>
<td>50.5</td>
<td>0.353</td>
<td>+/-1.5</td>
<td>+/-15.0</td>
<td>&lt; 3.7</td>
<td>In-package 1 layer balun</td>
</tr>
<tr>
<td>[3]</td>
<td>9.0</td>
<td>0.600</td>
<td>0.6</td>
<td>0/unable</td>
<td>&lt; 8.5</td>
<td>IHP SiGe BiCMOS 2 layer balun</td>
</tr>
<tr>
<td>[4]</td>
<td>12.0</td>
<td>0.165</td>
<td>~3</td>
<td>+/-30.0</td>
<td>6.0</td>
<td>350nm SiGe BiCMOS 1 layer balun</td>
</tr>
<tr>
<td>[5]</td>
<td>65.0</td>
<td>0.560</td>
<td>-1.6/0.6</td>
<td>+/-5.2</td>
<td>&lt; 7.0</td>
<td>180nm SiGe BiCMOS 2 layer balun</td>
</tr>
</tbody>
</table>

is highly reflected and there is little conversion between differential and common signals. The loss between single-ended port P1 and differential port is only about 1.9 (dB) at 40 (GHz).

IV. CONCLUSIONS
The paper has presented a rigorous analysis of an ideal Marchand balun to support an efficient tuning method that can be used at mm-wave frequency to fine-control and reduce the imbalance. The method takes advantage of the AC-ground that a Marchand balun requires for proper operation. The node is loaded by a susceptance $B_{P4}$ that ideally introduces a short circuit. The susceptance can be controlled to provide a suitable load to reduce the balun imbalance at the frequency of operation. The susceptance can be implemented with varactors and other controllable components whenever available to provide an effective tuning mechanism. At high frequency, losses may not allow a continuous control of the susceptance. Nevertheless, $B_{P4}$ can be properly designed for proper operation of the balun. Measurements of a Q band Marchand balun have been mixed with simulation results to discuss and support the tuning analysis. State-of-the-art performance of the balun has been demonstrated.

ACKNOWLEDGMENT
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REFERENCES
[8] L. Boglione and J. Goodman, “Performance of a Marchand balun at Q band in Silicon Germanium (SiGe) technology,” 2014 IEEE 8th German Microwave Conference (GeMiC), March 10-12 2014, Aachen, Germany.

Fig. 6. Mixed mode performance of the Marchand balun. The solid black line shows the Momentum simulation results. Port P4 is properly terminated by a combination of small capacitor $C_N$ + line + large capacitor such that an AC-short is effectively loading the balun’s T-junction.