CMOS on-chip stacked Marchand balun for millimeter-wave applications

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Abstract: A millimeter-wave CMOS on-chip stacked Marchand balun is presented in this paper. The balun is fabricated using a top pad metal layer as the single-ended port and is stacked above two metal conductors at the next highest metal layer in order to achieve sufficient coupling to function as the differential ports. Strip metal shields are placed underneath the structure to reduce substrate losses. An amplitude imbalance of 0.5 dB is measured with attenuations below 6.5 dB at the differential output ports at 30 GHz. The corresponding phase imbalance is below 5 degrees. The area occupied is $229\ \mu\text{m} \times 229\ \mu\text{m}$.

Keywords: millimeter-wave, CMOS, Marchand balun, substrate losses

Classification: Microwave and millimeter wave devices, circuits, and systems

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1 Introduction

Advancements in CMOS processes have enabled device integrations and the realization of high speed applications. Many potential applications utilize wireless transmissions that require analog RF front end, including balanced mixers and differential amplifiers. In these circuits, baluns are required for conversions between differential balanced signals and single-ended unbalanced signals. As a result, on-chip CMOS baluns have been reported in recent works [1, 2]. On-chip balun offer high levels of integration for cost-savings and develop less parasitic due to shorter interconnections to devices. As a result, they are suitable for high frequency applications. It is, however, a challenge to obtain good performances with low losses when designing the balun on standard lossy silicon substrates. In addition, the balun should occupy a small area and maintain design simplicity. In this work, due to the broadband nature of the Marchand-type balun used, the design parameters can be easily estimated without complex calculations or time-consuming simulations. Section 2 describes the balun structure and design considerations. Section 3 reports the measurement results of the work.

2 Balun Design

The objective of the design is to realize a feasible balun structure that can be implemented in a high frequency circuit. For rapid simulations and high design error tolerance, a wideband, passive Marchand-type balun is used. Figure 1 shows the design of the balun. The shape of the balun is optimized to reduce occupied area and minimizes the distance between the differential ports. The desired distance between the differential ports is closely affected by the layout requirements of the circuit that uses the balun. In general, a balun connects to the active devices through a minimum of interconnections, especially at high frequency. Therefore the differential ports are located close to the MOSFETs and to each other. Typical reported works of balun test

Fig. 1. Structure of the stacked on-chip balun includes the use of the top pad metal layer and two conductors on metal layer 6 with slotted shields placed below the metal.

structures occupy large area without an efficient shape for realization in a circuit [2].

This Marchand-type balun uses a thick top pad metal strip of half-wavelength. The single-ended port is at one end while the other end is left open-circuited. Two metal strips are located immediately under the top pad metal strip in the next highest metal layer. One end of each lower metal strip is connected to ground while the other end connects to each of the differential ports. This stacked structure allows the use of the thick top pad metal layer available in the process technology in a useful way, which normally is not suitable for carrying signals that are directly connected to the gate of the MOSFET, in order to satisfy the antenna rules. In addition, this stacked structure provides optimal inductive coupling, as compared to planar layout of the lines on the same metal layer. In this stacked design, all lines have the same width. Slotted ground shields are laid underneath the metal structures to prevent the electric field from penetrating the silicon substrate to induce substrate eddy currents.

The design of the balun requires determining the length of the top pad metal strip and the width. Each of the two lower metal strips has half the length of the top pad metal to be at a quarter-wavelength long, less the gap distance between the differential port outputs. Determining the length requires an estimate of the effective permittivity. The effective permittivity is related to the wavelength of the propagating signal according to Eq. (1).

$$\lambda = \frac{c}{f\sqrt{\epsilon_r}} \quad (1)$$

The value of the effective permittivity depends strongly on the structure of the transmission lines that forms the balun. For conventional microstrip line structure, the value is taken approximately at 4.0, using SiO₂. Transmission line structures using slow-wave designs are developed [3] which has an effective relative permittivity of up to 15, according to its wavelength reduction factor. The lines used in this work have an effective relative permittivity of 7.6 and this corresponds to a shorter wavelength with a reduction factor of 2.8 times when compared to conventional microstrip lines. Due to the broadband nature of the Marchand balun, Eq. (1) is sufficient to provide an estimate for design and further EM simulations can determine the width for the required impedance. In this design, the widths are 12 μm to obtain 50 Ω port impedances for measurements.

Finally, the position of the differential ports is determined by the gap distance required between them. It is necessary to consider the trade-off between placing them closely to minimize phase imbalance and placing them apart to reduce the parasitic capacitance. This design choice also considers the layout requirements of the circuit employing this device. In this design, a value of 10 μm is selected that is able to maintain good phase balance as well as amplitude balance as shown in the results in the next section.

3 Measured Results

The test structure is fabricated using a CMOS 90 nm 6M1P process connected to two GSGSG pads for measurements using Anritsu 37397D vector network analyzer with a SM6000 four-port test set. This setup results in one dummy port that is not used. Nevertheless, standard 4-port open-short-through calibration can be performed with the existing calibration structures without any loss of accuracy. The open-short de-embedding method is then employed to remove the effects of the pads and the additional lengths that connect to the balun ports. Ignoring the measurements of the dummy port, the 3-port S-parameter matrix of the balun is obtained.

Fig. 2. Transfer characteristics of the balun. Port 1 refers to the single-end port. Ports 2 and 3 the differential balanced ports.

Figure 2 shows the transfer characteristics of the balun. Port 1 refers to the single-ended port. Ports 2 and 3 refer to the differential balanced ports. $|S_{21}|$ and $|S_{31}|$ are the measured attenuations through ports 2 and 3 respectively. The theoretical values of $|S_{21}|$ and $|S_{31}|$ of an ideal balun are -3 dB, since each differential port divides to half of the power at the single-ended port. At 30 GHz, the measured values of $|S_{21}|$ and $|S_{31}|$ are -6.5 dB and -6.0 dB respectively. This calculates to an amplitude imbalance of 0.5 dB. Within an acceptable amplitude imbalance of ± 1 dB, the frequency range is between 22.4 GHz and 44.4 GHz. This large bandwidth indicates a good broadband amplitude balance.

Figure 3 shows the measured phase difference between the differential ports after de-embedding.

For the proper functioning of the balun, the desired phase difference between the differential ports is 180° . At 30 GHz, the measured phase difference is 185° . This calculates to a phase imbalance of 5.0° . This verifies the

Fig. 3. Phase difference between the differential ports of the balun. At 30 GHz, the phase imbalance between the two ports is below 5 degrees.

functionality of the balun at the millimeter-wave frequency. Within an acceptable phase imbalance of $\pm 10^\circ$, the frequency range is between 11.6 GHz and 37.3 GHz. Therefore, considering the acceptable amplitude imbalance of ± 1 dB in this frequency range, the balun operates well between 22.4 GHz and 37.3 GHz, confirming its broadband characteristics.

In order to analyze the use of the balun as an 180° power splitter, the common mode rejection ratio (CMRR) is calculated according to [4], and given in Eq. (2).

$$\text{CMRR} = \left| \frac{S_{dm}}{S_{cm}} \right| = \left| \frac{S_{31} - S_{21}}{S_{31} + S_{21}} \right| \quad (2)$$

S_{dm} and S_{cm} denote the differential-mode and common-mode S-parameters respectively. Eq. (2) gives a single measure of the effects of both magnitude and phase imbalance in a splitter that can be readily calculated from measured data. At 30 GHz, the CMRR has a value of 25.5 dB. In the frequency between 22.4 GHz and 37.3 GHz, the minimum CMRR is 21.0 dB.

When the balun is analyzed as an 180° power combiner, a rejection ratio cannot be directly applied. However, a common-mode combiner response ratio (RCM_{comb}) and a differential-mode response ratio (RDM_{comb}) are defined by Eq. (3) and Eq. (4).

$$\text{RCM}_{\text{comb}} = \frac{1}{\sqrt{2}} |S_{12} + S_{13}| \quad (3)$$

$$\text{RDM}_{\text{comb}} = \frac{1}{\sqrt{2}} |S_{12} - S_{13}| \quad (4)$$

The common-mode signal, measured by RCM_{comb} , is undesired and will affect the output of the combiner when there is an imbalance. The RDM_{comb} is the desired response of the combiner. Eq. (3) can be derived by expressing the output voltage wave as a ratio of the common-mode input voltage wave.

Similarly, Eq. (4) can be derived by expressing the output voltage wave as a ratio of the differential-mode input voltage wave. From measurement results, the RCM_{comb} of the fabricated balun is -28.7 dB at 30 GHz and the RDM_{comb} is -3.2 dB at 30 GHz. The values and equations can be verified using the identity of Eq. (5).

$$\text{CMRR} = \frac{\text{RDM}_{\text{comb}}}{\text{RCM}_{\text{comb}}} \quad (5)$$

The measurement results compare well with works on reported baluns. In [1], the balun operates from 25 GHz to 40 GHz designed for $0.24 \mu\text{m}$ SiGe BiC-MOS and occupies $285 \mu\text{m} \times 1333 \mu\text{m}$. In [2], the balun operates from 800 MHz to 2.5 GHz designed for $0.18 \mu\text{m}$ CMOS and occupies $250 \mu\text{m} \times 250 \mu\text{m}$.

4 Conclusion

An on-chip stacked Marchand balun has been realized using CMOS 90 nm process technology for potential applications in the millimeter-wave frequency band. The balun structure has been optimized for the process design rules by employing the top pad metal and thin slotted ground metal shields. As a result, it consumes a small area of $229 \mu\text{m} \times 229 \mu\text{m}$. At 30 GHz, the measurements show an amplitude imbalance of 0.5 dB and a phase imbalance of 5.0° . The balun operates within an amplitude imbalance of ± 1 dB and a phase imbalance of $\pm 10^\circ$ between 22.4 GHz and 37.3 GHz.

Acknowledgments

The VLSI chip in this study has been fabricated through the chip fabrication program of VLSI Design and Education Center (VDEC), the University of Tokyo, with the collaboration by STARC, Fujitsu Limited, Matsushita Electric Industrial Company Limited., NEC Electronics Corporation, Renesas Technology Corporation, and Toshiba Corporation.