5.7 GHz Gilbert I/Q Downconverter Integrated With a Passive LO Quadrature Generator and an RF Marchand Balun

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***Abstract*—A 5.7 GHz I/Q downconversion mixer is demonstrated in this letter using 0.35 μm SiGe BiCMOS technology. A quarter-wavelength coupled line and two center-tapped transformers are utilized to generate differential quadrature LO signals. A miniaturized Marchand balun is placed before the common-base-configured RF input stage of each I/Q Gilbert mixer to generate balanced RF signals. All the reactive passive elements are placed directly on the standard silicon substrate. The 5.7 GHz I/Q downconverter achieves 7 dB conversion gain, -26 dBm IP_{1dB}, and -18 dBm IIP_3 at the power consumption of 3.875 mW and 2.5 V supply voltage.**

***Index Terms*—Gilbert mixer, I/Q downconverter, Marchand balun, SiGe BiCMOS.**

I. Introduction

In many applications, generating accurate quadrature signals for quadrature up/down conversion mixers [1] and sub-harmonic mixers [2] is always a challenge. Poly-phase filters are used to generate differential quadrature signals from a differential signal. In general, many sections of poly-phase filters are employed to tolerate the process variations on resistors and capacitors at the cost of higher loss. The use of reactive passive components is another choice to generate differential quadrature signals especially at high frequencies. In the past, quadrature signals generated with reactive passive components were implemented on the GaAs semi-insulating substrate and high-resistive silicon substrate [3]. There is a need to integrate the quadrature coupler in the standard silicon process for the silicon radio frequency integrated circuit (RFIC) era. Thus, the quadrature coupler has been demonstrated by using interconnect metals with ground shielding plane to avoid the substrate loss in the standard silicon process [4]. However, the low dielectric constant of the interconnect dielectrics results in a large size quadrature coupler. It is benign to take advantage of the high silicon dielectric constant. However, the high substrate loss in a standard silicon process leads to amplitude imbalance between the coupling port and through port in a quadrature coupler. It is difficult to employ a quadrature coupler with large amplitude imbalance.

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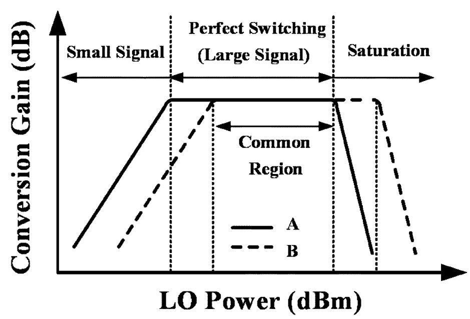

Fig. 1. Conversion gain versus LO power of two identical Gilbert mixers (A and B) with different LO path loss.

Recently, a Marchand balun consisting of two quadrature couplers has been demonstrated directly on lossy silicon substrate [5]. The demonstrated Marchand balun has balanced output signals even though each constituent quadrature coupler has unbalanced outputs.

In this letter, the use of a quadrature coupler directly on the lossy silicon substrate is employed in the local oscillation (LO) ports of a Gilbert I/Q downconverter. The impact of quadrature generator amplitude imbalance is minimized through proper choice of the LO input power. A Gilbert mixer, especially with a bipolar mixing core [5], has a region of flat gain as a function of the LO input power because only several times of the thermal voltage is needed to make current commutate in emitter-coupled differential pairs. Fig. 1 illustrates the conversion gain versus LO input power for two identical Gilbert mixers with different LO path loss. The curve B in Fig. 1 is the right-shifted version of the curve A because the LO path loss of the curve B is larger than that of the curve A. It shows that the Gilbert mixer is tolerant of different LO path loss if the LO input power is in the common overlapped range shown in Fig. 1.

II. Circuit Design

Applying this concept to the I/Q downconverter design, we can achieve perfect current switching in both I/Q paths by properly choosing LO input power while a quadrature signal generator is employed in the LO stage with perfect phase relations at the desired frequency but unequal amplitude caused by different LO path loss. In this work, the quadrature generator is composed of a quarter-wavelength coupled line and two transformers as shown in Fig. 2. The LO signal is injected at the incident port of the quarter-wavelength coupled line. The LO ports of the I-channel mixer are connected to the coupling port through the subsequent transformer while the through port

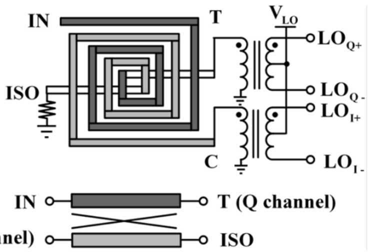

Fig. 2. LO quadrature signal generator using a quarter-wavelength coupled line and two center-tapped transformers.

is connected to the LO ports of the Q-channel mixer through the other transformer. This type of quadrature generator has been implemented in the LO stage, but the intrinsic loss imbalance caused by the lossy silicon substrate in the differential quadrature generator makes I/Q channel IF outputs obviously unequal.

The schematic of the I/Q downconverter utilizing an LO differential quadrature signal generator and an RF Marchand balun is shown in Fig. 3. The Marchand balun is employed in the RF stage to convert an unbalanced signal into two balanced signals in spite of the lossy silicon substrate [5], [6]. A planar Marchand balun, consisting of two back-to-back quarter-wavelength coupled lines, has both coupling ports connected with short ends, the incident port in the opposite quarter-wavelength coupled line left open while the signal is incident in the input incident port and two balanced signals appear at the two isolated ports as shown in Fig. 3. The Marchand balun is followed by the common-base-configured transistors, $Q_1 - Q_4$, for I/Q channels because of their excellent frequency response and convenience for broadband impedance matching. The short ends in the coupling ports of the Marchand balun are also utilized as the dc return ground of the common-base-configured transistors, $Q_1 - Q_4$. Each quarter-wavelength coupled line in the Marchand balun is replaced by its shunt C- series L-shunt C lumped versions [7] as shown in Fig. 3 to further reduce the Marchand balun size at the cost of narrower bandwidth. The center frequency of each lumped quarter-wavelength coupled line used in the Marchand balun of the RF stage is designed around 5.7 GHz. This lumped-type quadrature coupler can also be employed in the LO port to further reduce the chip size at the cost of bandwidth.

The photograph of the proposed I/Q downconversion mixer is shown in Fig. 4. The die size is 1×1 mm^2 and is dominated by the passive elements consisting of a Marchund balun, a quarter-wavelength coupled line and two transformers. The emitter size of all the SiGe HBTs in common-base-configured transistors $(Q_1 - Q_4)$ and Gilbert mixer core $(Q_5 - Q_{12})$ are 0.3 μm in width and 1.9 μm in length, respectively. A PMOS current mirror load is employed in each I/Q downconversion mixer to combine two differential signals into a single-ended output. A common-collector output buffer in each IF port is designed to facilitate the on-wafer measurement. In order to shrink the size of the quarter-wavelength coupled line employed in the LO differential quadrature generator, the interleave transformer type quarter-wavelength coupled lines are employed as shown in Fig. 2. The LO quadrature coupler has 7 μm line width, 3 μm line spacing and outer diameter of 266 μm to generate the

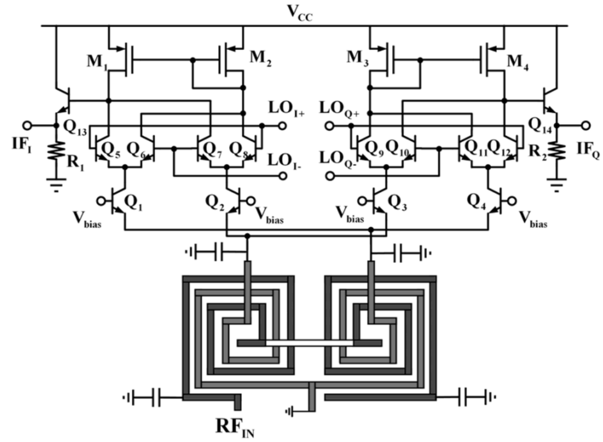

Fig. 3. Schematic of the SiGe BiCMOS I/Q downconverter with a reactive passive LO quadrature signal generator and an RF Marchand balun. The LO quadrature generator is shown in Fig. 2.

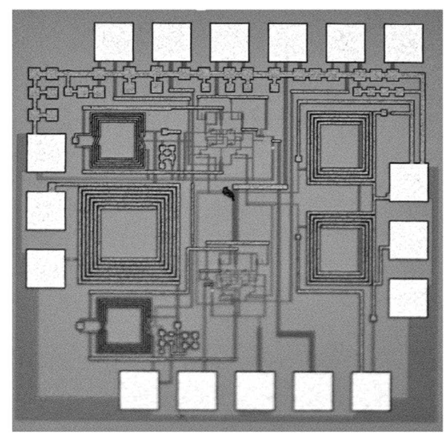

Fig. 4. Photograph of the SiGe BiCMOS downconverter with a reactive passive LO quadrature signal generator and an RF Marchand balun.

quadrature phase in coupling and through ports around 5.7 GHz. There are two 2:3 transformers following the quadrature coupler. Each transformer consists of two constituent inductors with line width, line spacing, and outer diameter of 2.6 μm, 1.8 μm, and 140 μm, respectively. The dc bias voltage for the LO port is fed from the center-tapped point in the secondary coil of the transformer. On the other hand, the size of three-section 5–6 GHz poly-phase filter is about 180×180 μm^2 with 9.3 dB loss by calculating the RC values in [8].

III. Measurement Performance

The fabricated SiGe BiCMOS quadrature downconverter with the single-ended LO, RF, and IF ports is convenient for on-wafer measurements. The supply voltage is 2.5 V and the total power consumption is 3.875 mW. The measured I and Q channel IF outputs have flat gain regions for LO power ranging from -10 dBm to 1 dBm, and -7 dBm to 3 dBm, respectively, when RF=5.7 GHz, LO=5.665 GHz and IF= 35 MHz. In other words, the coupling port has about 3 dB more loss than the through port has in the quadrature coupler. The conversion gain difference between I and Q channels varies within 1 dB for LO power from -7 dBm to 1 dBm as shown in Fig. 5. Fig. 6 shows the power performance of the downconverter for each I/Q

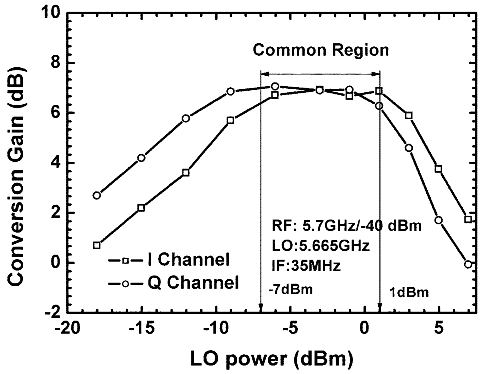

Fig. 5. I/Q channel conversion gain versus LO input power of the SiGe BiCMOS I/Q downconverter with a reactive passive LO quadrature signal generator and an RF Marchand balun.

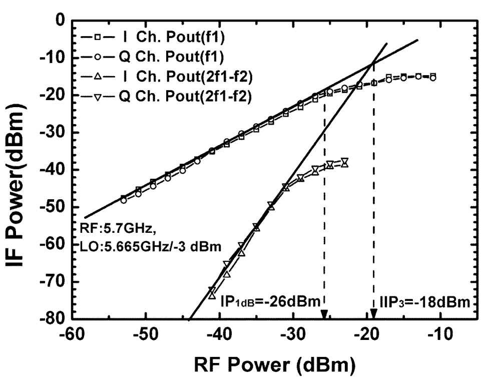

Fig. 6. Power Performance of the SiGe BiCMOS I/Q downconverter with a reactive passive quadrature signal generator and an RF Marchand balun.

channel. 7 dB conversion gain, -26 dBm IP_{1dB}, and -18 dBm IIP_3 are achieved for both I/Q outputs. The IF bandwidth of the SiGe BiCMOS I/Q downconverter is 120 MHz as shown in Fig. 7. The measured I/Q downconverter output waveforms are shown in Fig. 8. The average phase error is below 2° and amplitude error is below 0.3 dB. The RF input return loss is better than 10 dB from 4 to 7 GHz. The measured double sideband noise figure is 20 dB. The I/Q channel performance of the demonstrated downconverter is well balanced in spite of the unbalanced LO path loss caused by the substrate loss. On the other hand, the use of a quadrature generator in the RF path results in a 2 dB amplitude imbalance for I/Q channel output as shown in [9], [10]. The insertion loss of 7 dB, magnitude imbalance of 4 dB and phase error of 2° from 5–6 GHz were measured for the quadrature coupler in [10].

IV. Conclusion

A quarter-wavelength coupled line and two transformers are employed in the LO input stage to generate differential quadrature signals on a standard silicon substrate. The Marchand balun in the RF stage provides balanced RF signals and serves as the dc return path for the common-base-configured transistors. The 0.35 μm SiGe BiCMOS Gilbert downconverter at 5.7 GHz with the integrated passive quadrature LO generator and RF Marchand balun has been demonstrated in a standard silicon process

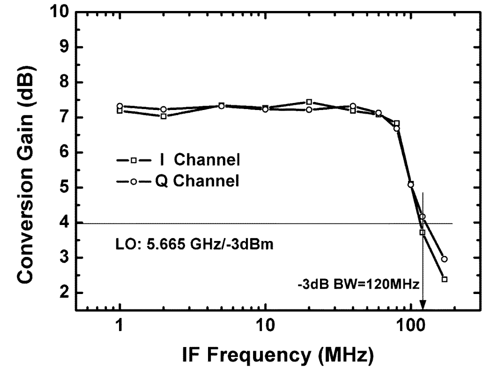

Fig. 7. IF bandwidth of the SiGe BiCMOS I/Q downconverter with a reactive passive quadrature signal generator and an RF Marchand balun.

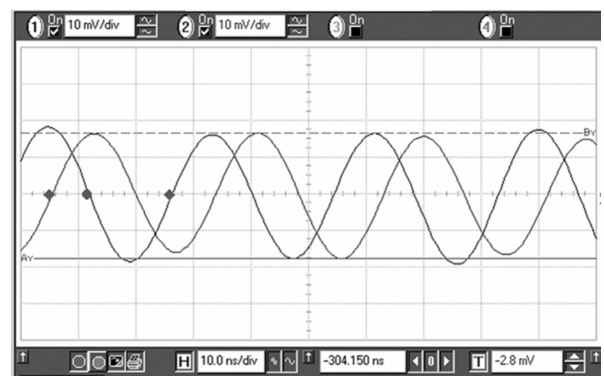

Fig. 8. Output waveform of the SiGe BiCMOS I/Q downconverter with a passive LO quadrature signal generator and an RF Marchand balun.

by choosing appropriate LO input power in spite of the unbalanced LO path loss caused by the substrate loss.

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